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07-08 July-August 2025 | Volume 20

SIMULATION | TEST

Vehicle under Test

INCLUDING
The Hansen Report on Automotive Electronics

SIMULATION
Accelerated with FPGA-based Architecture

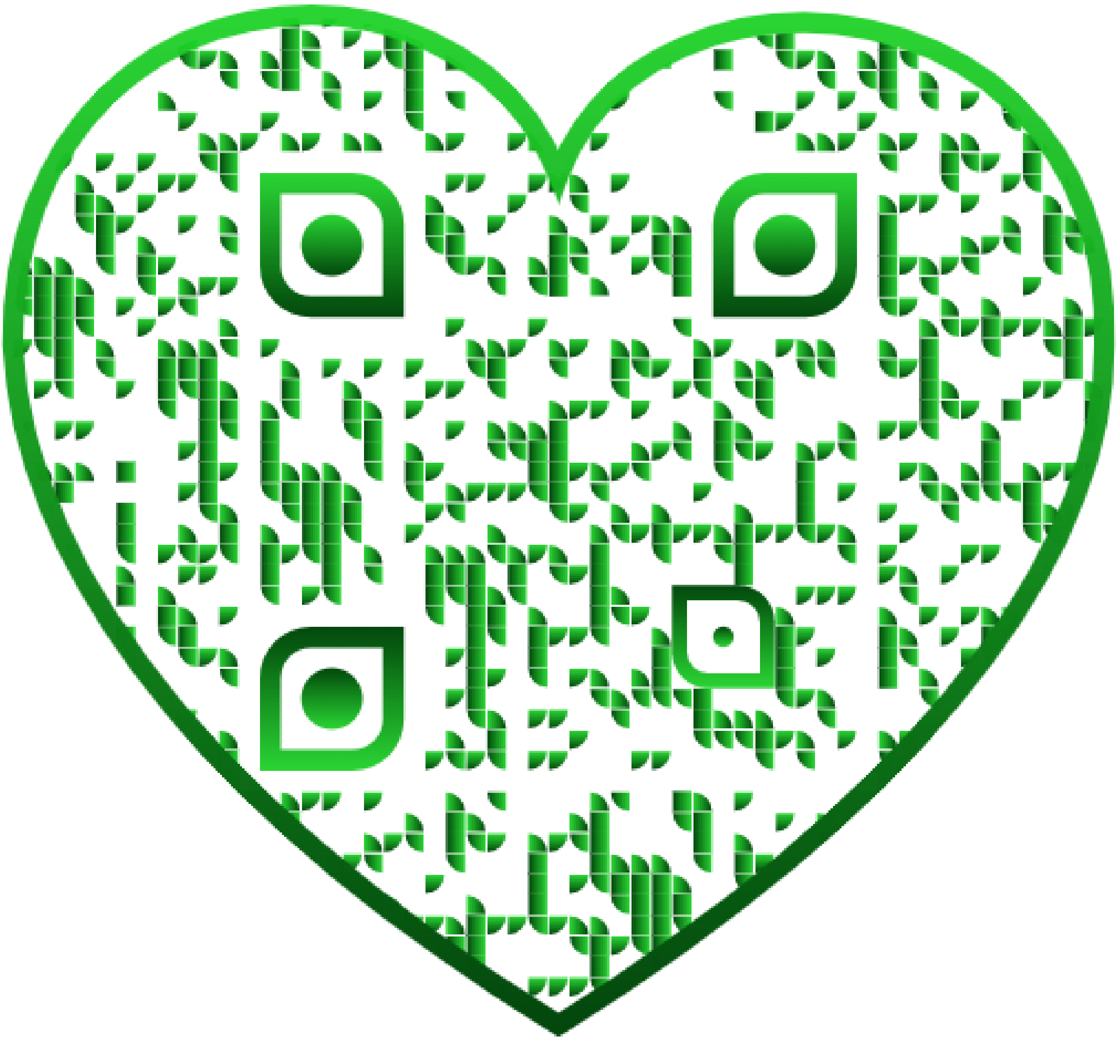
TEST SYSTEM
Used for End-to-End Software Validation

SOFTWARE-DEFINED VEHICLE
Opens up New Possibilities for Testing ADAS/AD Functions

ATZextra
Electric Mobility

/// IN THE SPOTLIGHT Hydrogen in Motor Racing

/// GUEST COMMENTARY Steven Peters [TU Darmstadt]



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AUTOMATED DRIVING and Dynamic Model for Driver Monitoring
/// INTERVIEW Carina Kießling [Roland Berger]

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Triple Trouble?

Dear Reader,

Electric mobility is an exciting topic, as you can see in the ATZextra section starting on page 44 of this magazine. Unfortunately, the exciting aspects are not only associated with e-mobility itself, but also include the economic pitfalls it holds. The topic of the century is causing a lot of trouble: The simultaneous switch to software-centric architectures is known to tie up considerable additional resources. Even if we disregard the latter factor, we discover suboptimal areas that still result from the Diess & Co. era, with its overly positive “no dents allowed – always forward, never backward” aspiration of many company management teams when it comes to capacity expansion and attempts to completely abandon combustion engines which were considered outdated at the time. Looking at indicators such as the insolvency of Northvolt, the great hope for European battery production, the coming Chapter 11 filing by Wolfspeed, a player in power electronics, and the problems of Tier-1 suppliers ranging from ZF to Bosch, we can’t paint a rosy picture. OEMs are also under pressure, and this tbh does not even already include job cuts resulting of the switch from combustion engines to electric cars featuring fewer parts, but rather a “go all-in on electric, but we’re selling far too few” effect. Is this still a double dip or is it turning into a triple dip?

If you add in the European Union’s IPCEIs for semiconductors, which were introduced in response to the Covid supply chain bottlenecks, there is reason to fear the latter. The electronics sector, in particular, will become expensive and tie up large resources in the long term, depending on how much suffering the 27 EU states are willing to endure. The situation seems dire, although looking back at the long gone 2008 crisis and the rapid recovery back then that defied all expectations could offer some consolation. On the other hand, unfortunately, every new crisis brings with it more factors than the previous one: Currently, these include the arbitrary US tariffs that are going wild some and then, even rising or falling by a factor of 10 on felt daily basis, blockades on rare earths, and a war raging in the middle of Europe. If the automotive market continues to function as it is currently doing despite the last few lines, we can only congratulate ourselves every now and then that the whole system hasn’t completely fallen apart yet and bravely carry on no matter how troubled the waters currently are.

Enjoy reading this issue.

Robert Unseld

Robert Unseld
Responsible Editor

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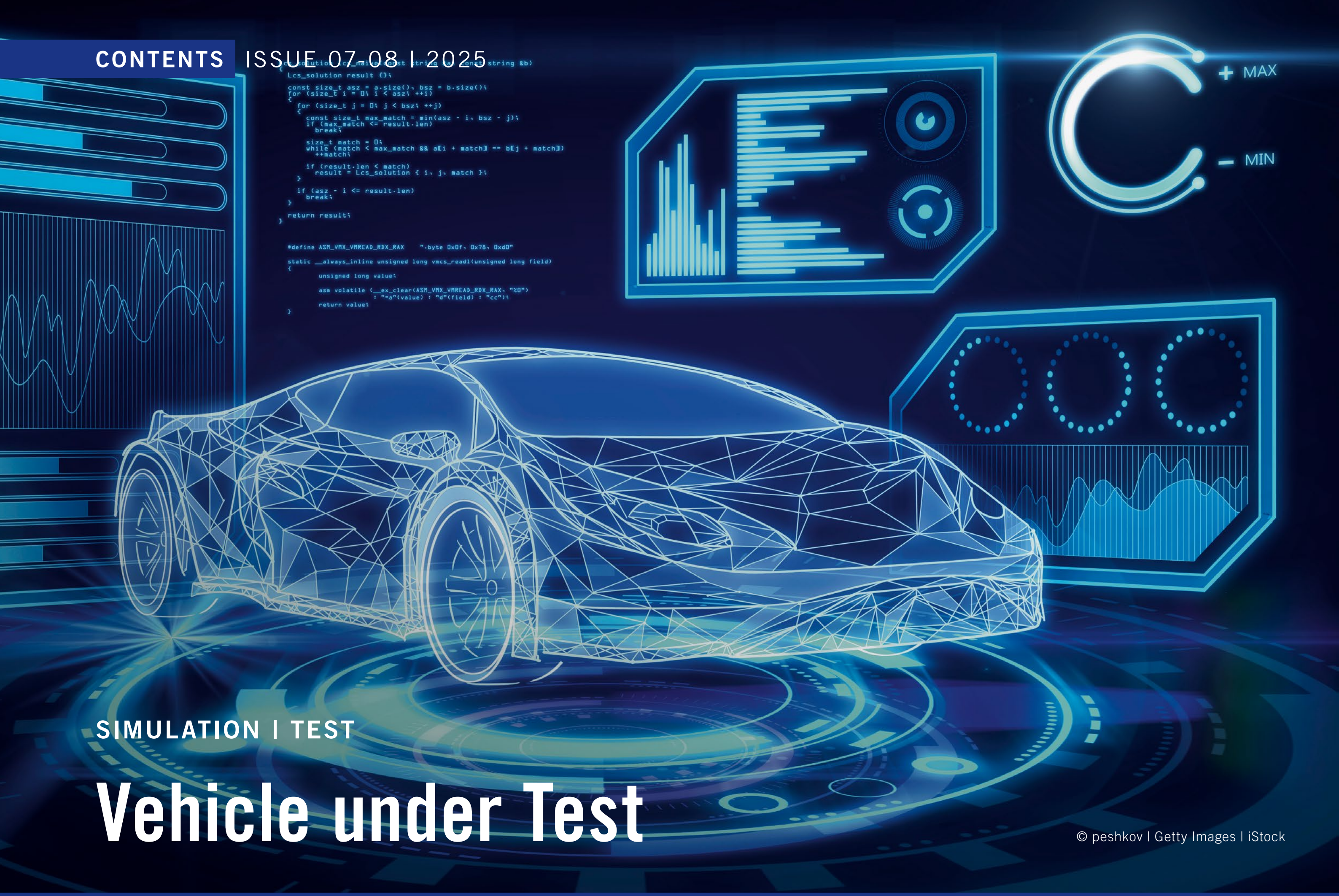

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SIMULATION | TEST

Vehicle under Test

The shift toward software-defined vehicles is increasing the number of functions that need to be developed and tested in vehicles. Since the necessary redesigned E/E architecture must also be simulated and tested with regard to its changeability, the test systems used must be just as agile and modular as the test objects themselves. This also provides the option of checking and optimizing functions at a very early stage and eliminating (real) test sequences.

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Alexander Heintzel

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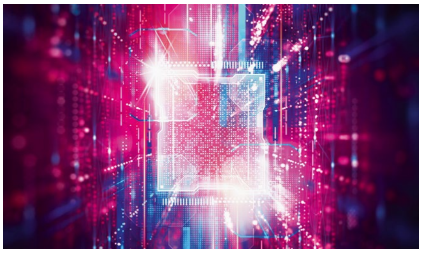
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8 Fast integration of soft- and hardware solutions into vehicles is paramount. ITK Engineering has developed an FPGA-based accelerator architecture for this.

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20 FEV.io shows how SDVs enable dynamic configuration and enhancement of vehicle functionality without the need for hardware modifications.

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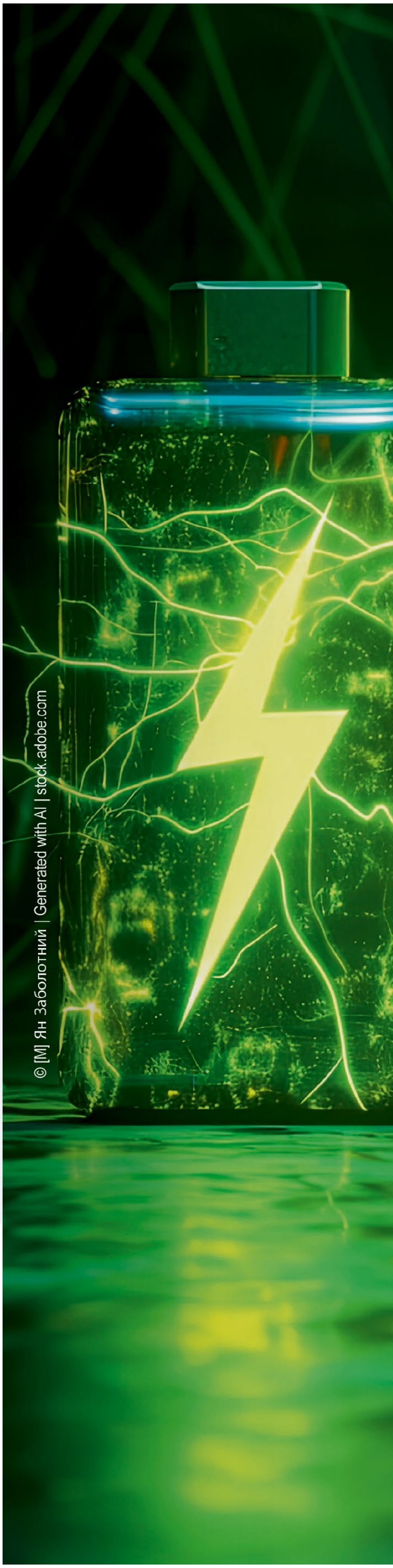
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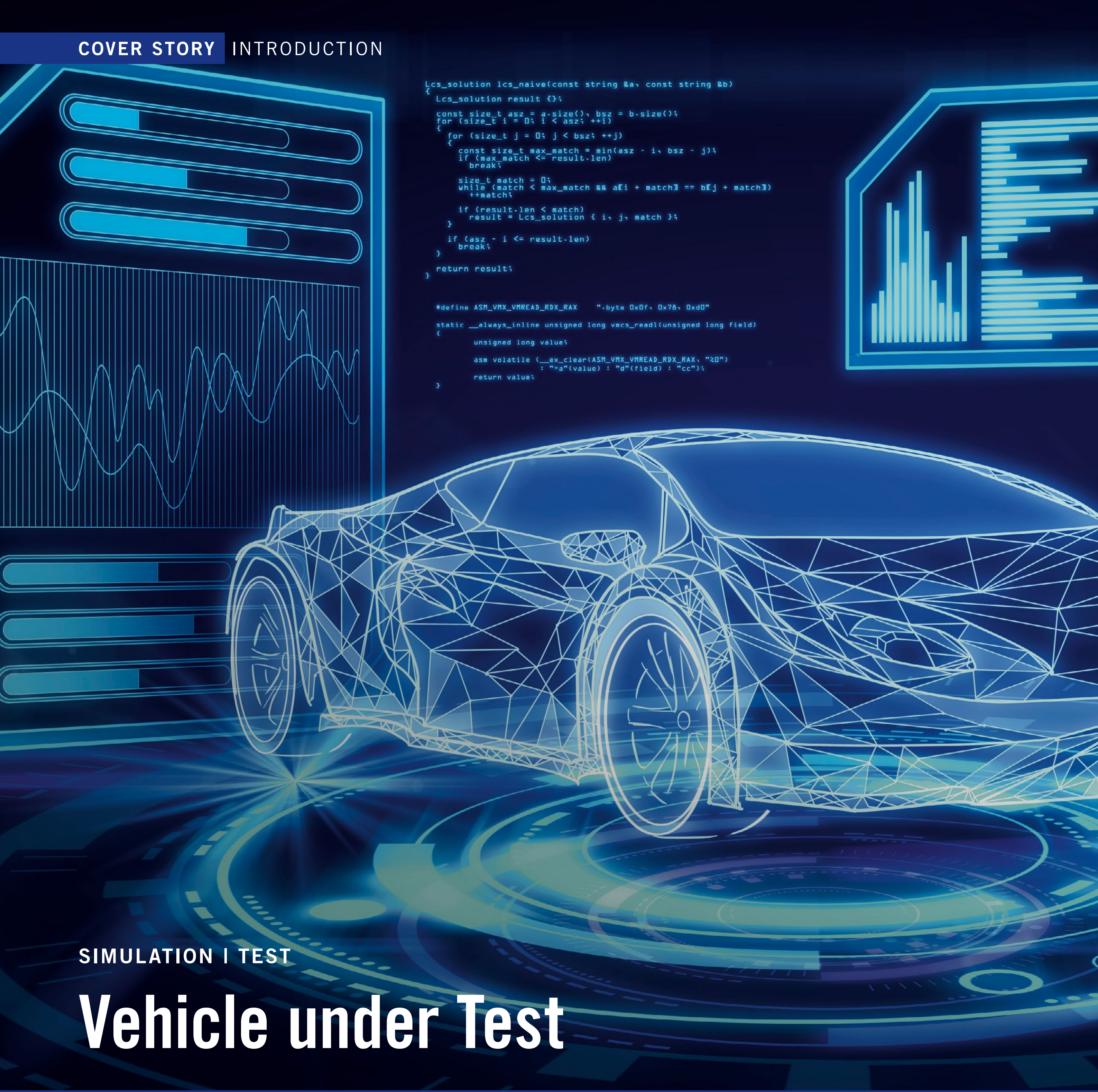

```
Lcs_solution lcs_naive(const string &a, const string &b)
{
  Lcs_solution result {};

  const size_t asz = a.size(), bsz = b.size();
  for (size_t i = 0; i < asz; ++i)
  {
    for (size_t j = 0; j < bsz; ++j)
    {
      const size_t max_match = min(asz - i, bsz - j);
      if (max_match <= result.len)
        break;

      size_t match = 0;
      while (match < max_match && a[i + match] == b[j + match])
        ++match;

      if (result.len < match)
        result = Lcs_solution { i, j, match };
    }

    if (asz - i <= result.len)
      break;
  }

  return result;
}


  #define ASM_VMX_VMREAD_RDX_RAX    ".byte 0x0f, 0x78, 0xd0"

  static __always_inline unsigned long vmcs_readl(unsigned long field)
  {
          unsigned long value;

          asm volatile (__ex_clear(ASM_VMX_VMREAD_RDX_RAX, "%0")
                        : "=a"(value) : "d"(field) : "cc");
          return value;
  }
```

SIMULATION I TEST

Vehicle under Test

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20 Managing Future Standards for the Thermal Propagation of Lithium-ion Batteries
Thorsten Decker, Jörg Kottig, Max-Arno Meyer [FEV.io]

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The need for sustainable mobility and the desire for automated driving have led to a turn in the automotive industry. It is getting harder to quickly integrate complex software and hardware solutions into vehicles over-the-air, especially during their lifetime. This not only has legal implications, because vehicles would soon no longer comply with homologation standards, but also increases the number of functions that need to be developed and tested in the vehicle.

The software-defined vehicle approach helps here, as its system architecture enables dynamic configuration and continuous addition of vehicle functions without hardware modifications. In light of this development, the twin disciplines of simulation and test are becoming even more relevant. Only simulations offer the possibility of checking and optimizing functionalities at an early stage of development and thus controlling test sequences in a targeted manner so that they can provide the necessary results and feedback. That saves time and money.

However, existing simulation infrastructures are increasingly reaching their limits, and previous validation and verification strategies are no longer sufficient. Simulations must therefore be accelerated across the board, while the developed software must be validated and verified in a time- and cost-saving manner. SDV speeds up the development dynamic.

Alexander Heintzel

Springer Professional

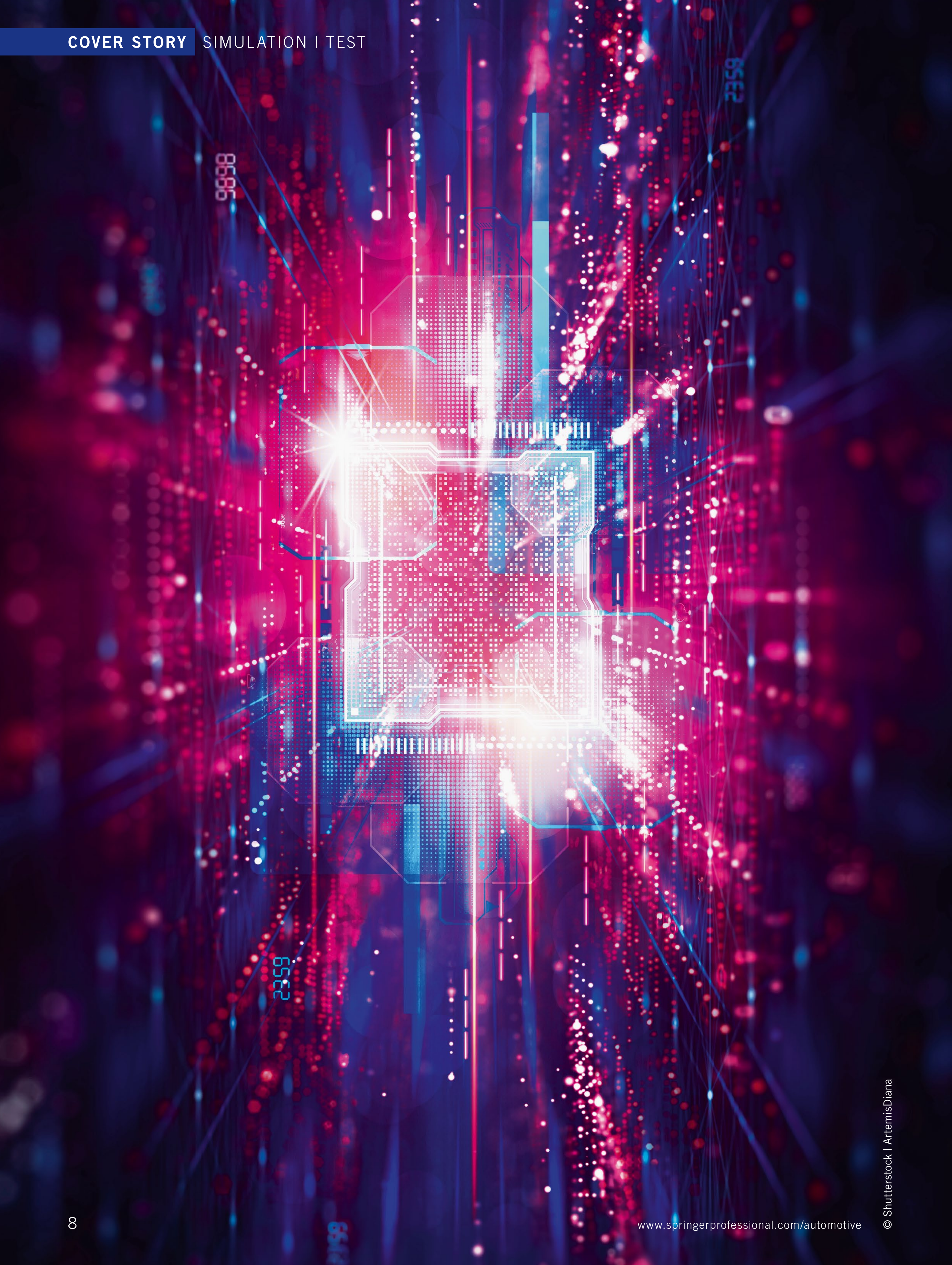
Simulation and Testing

Magazine Article: Zhu, B. et al.: Perception Sensor Model Fidelity Evaluation for Automated Driving System Scenario-Based Simulation Testing
https://www.springerprofessional.de/link/50777930

Magazine Article: Lorbeck, R.; Schutting, E.: Utilization of battery analysis methodologies for parametrization and enhancement of an electrochemically approximated simulation model approach for thermal management battery system tests
https://www.springerprofessional.de/link/50827234

Magazine Article: Nibbagandla, H.-K.: Continuous Integration and Testing of Software for Electric Powertrains
https://www.springerprofessional.de/link/50910244

You can find more about this topic in the magazines of the ATZ/MTZ Group and in our online portal www.springerprofessional.de/en



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Accelerated Simulations Using FPGA and FMI Technology

Integrating complex software and hardware solutions faster into modern vehicles is very important for the automotive industry. Simulations offer an opportunity to test and optimize this at an early stage. However, existing simulation infrastructures are reaching their limits. ITK Engineering has developed an accelerator architecture that significantly speeds up existing simulations using field-programmable gate arrays.

WRITTEN BY

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(Germany).

Modern vehicles are based on increasingly complex software and hardware solutions. Simulations make it possible to verify the integration and interactions between individual software components right from the start of development. As a result, the use of simulations continues to grow, while their setups are becoming increasingly complex and extensive. With the shift toward continuous development processes, the number of tests and scenarios required is continuing to rise. In order to meet the increasing requirements without delaying the development process, fast execution times are critical. But which factors have a lasting impact on speed?

Simulations in the context of system simulation for the design and verification of software must consider aspects of software-system interaction, such as emergency brake assist, recuperation, or lane change features. These operations involve numerous software components that interact with mechatronic components or the vehicle's surrounding environment. Simulation artifacts are created in order to calculate this. These may include models of physical elements such as actuators, sensors, or representations of control units and their software, known as virtual Electronic Control Units (vECUs).

SIMULATION PROCESS ON A COMPUTER

To represent system interactions, a large number of artifacts must be processed. Co-simulation frameworks are used for this purpose. In the automotive industry, software tools such as Simulink are commonly employed, typically running on Windows or Linux operating systems. These programs have the task of calling up the individual artifacts, performing the calculations, and managing data exchange.

Due to memory abstraction in modern operating systems, these programs do not have direct access to the processor's memory allocation. This leads to performance issues during the execution of the simulation, particularly when artifacts exchange data at high rates (for example in the MHz range), as in the case of simulating electrical processes. Because of the limited capacity of fast internal memory, such as the L1 or L2 cache, most read and write operations during simulation are handled by slower dynamic memory, **FIGURE 1**. This often results in unacceptably long execution times. Consequently, precise electrical interactions, such as those that occur in the control of electric machines, are frequently simplified in simulations, reducing accuracy.

In the near future, the increase in computing resources in vehicles with more powerful microcontrollers and new System-on-Chips (SoCs) will further exacerbate this problem. On the one hand, this leads to a greater number of software lines to execute. On the other hand, these SoCs include specialized integrated accelerators for tasks such as sensor data processing or cryptographic operations. This will further reduce simulation performance. The brute-force approach of using cloud CPU resources will not remain sustainable over the long term, either technologically or economically.

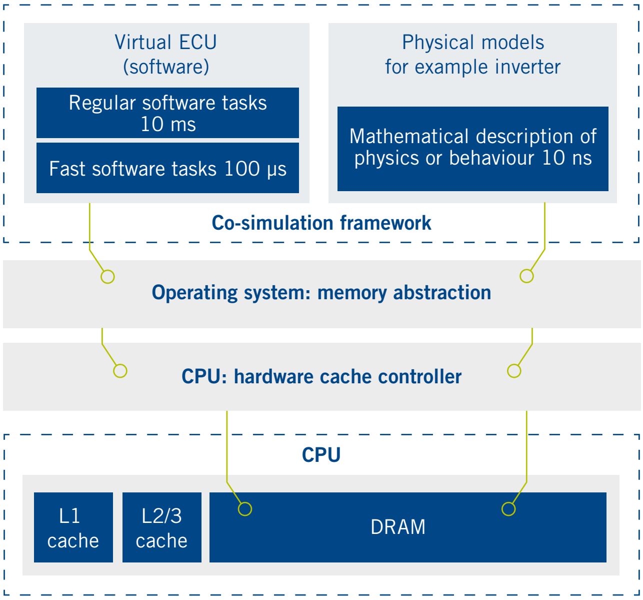

Virtual ECU
(software)
Regular software tasks
10 ms
Fast software tasks 100 µs
Physical models
for example inverter
Mathematical description of
physics or behaviour 10 ns
Co-simulation framework
Operating system: memory abstraction
CPU: hardware cache controller
CPU
L1
cache
L2/3
cache
DRAM

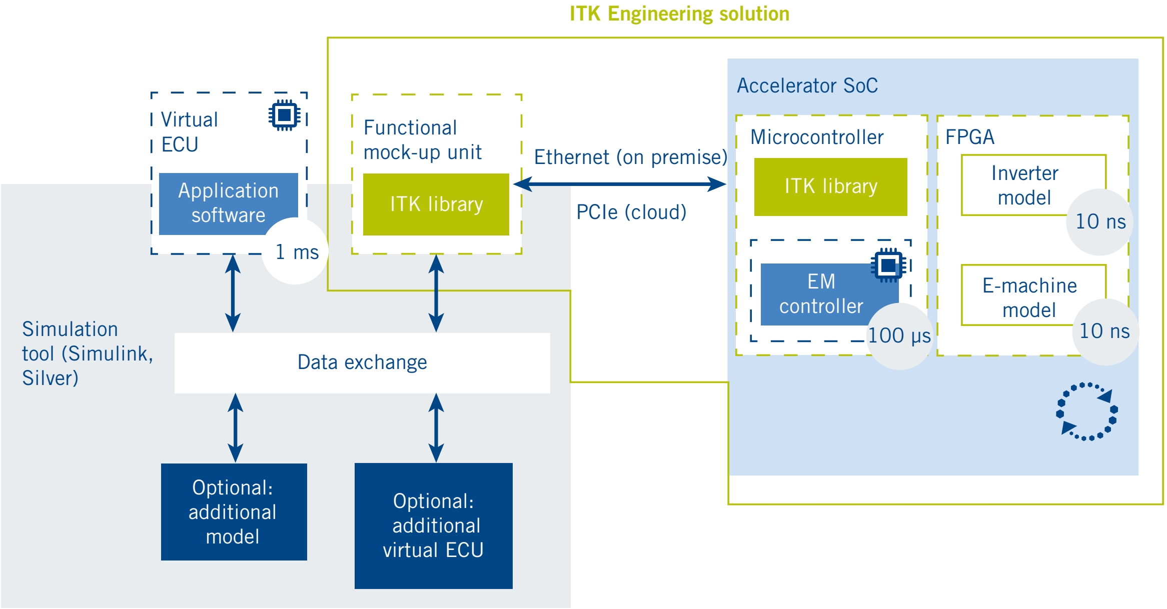
FIGURE 1 Memory flow diagram for simulations (© ITK Engineering)

IMPROVING SIMULATION SPEED

FIGURE 2 illustrates a simplified example of an architecture based on an inverter. To gain better control over computational resources in a simulation architecture with an operating system, ITK Engineering has introduced the concept of a hardware accelerator for co-simulation frameworks. The core idea is to offload computationally intensive tasks, such as electrical models of e-machines, to external accelerator hardware. The team selected Field-programmable Gate Arrays (FPGAs) as the external computing resource. This flexible acceleration architecture can be tailored to specific tasks such as solving mathematical models or user-defined algorithms.

Thanks to their hardware-related design, FPGAs can process data with minimal delay, making them ideally suited for real-time simulations. Similar approaches have been used in Hardware-in-the-Loop (HiL) systems for many years but have not yet been used for virtual Software-in-the-Loop (SiL) systems.

FIGURE 2 Architecture of the local acceleration setup (© ITK Engineering)


ITK Engineering solution
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ECU
Application
software
1 ms
Functional
mock-up unit
ITK library
Ethernet (on premise)
PCIe (cloud)
Accelerator SoC
Microcontroller
ITK library
EM
controller
100 µs
FPGA
Inverter
model
10 ns
E-machine
model
10 ns
Simulation
tool (Simulink,
Silver)
Data exchange
Optional:
additional
model
Optional:
additional
virtual ECU

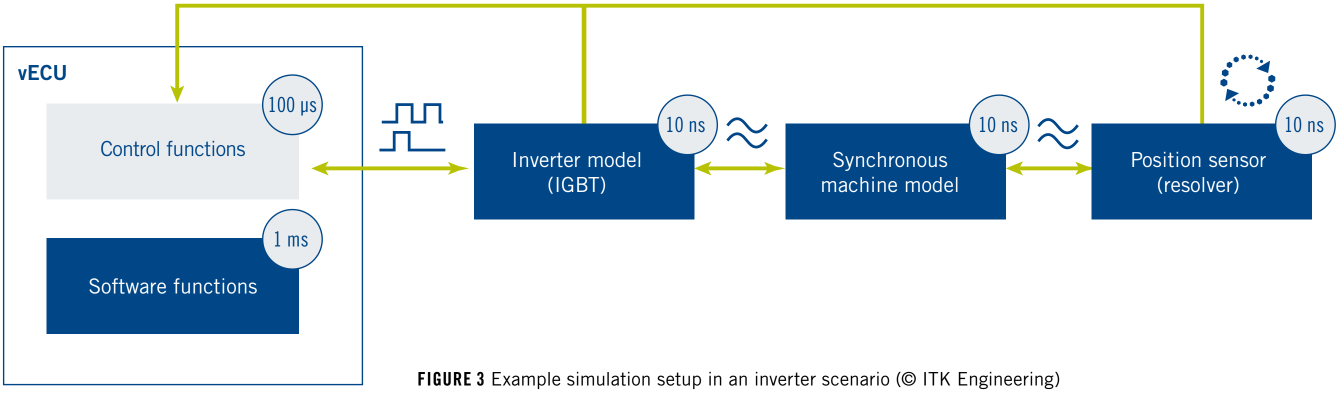

FIGURE 3 Example simulation setup in an inverter scenario (© ITK Engineering)

Various co-simulation programs such as CANoe, Cosym, Simulink, and Silver are used in industry. However, these programs lack a standardized interface for exchanging data during runtime. The aim was to develop a concept that could be integrated into customers' existing co-simulation frameworks in a way that is as user-friendly as possible and with minimum effort.

There is a standard, the Functional Mock-up Interface (FMI), which provides a unified interface for the seamless integration and co-simulation of models in different simulation environments. Since every framework such as CANoe, Cosym, Silver, or Simulink can integrate this interface, the idea emerged to use FMI to connect to an external accelerator. From the user's perspective, the model to be accelerated, executed on the FPGA, is an FMI artifact with input and output ports. However, the FMI artifact is only used for data exchange. The calculation of the model takes place on the accelerator, **FIGURE 2**.

To test this concept, the development teams decided to implement it in a test setup, using it to verify the control algorithm of an inverter ECU they had developed in-house. This example is suitable for the acceleration concept, as detailed inverter simulations need to precisely resolve PWM signals with approximately 20 KHz switching frequencies in order to accurately calculate the inverter, the e-machine model (for example synchronous machine model), and often a position sensor in real time with a typical simulation step size of approximately 10 µs. The setup, **FIGURE 3**, consists of the control unit software and various models. In the architecture, the control algorithm for current and speed regulation is called periodically every 100 µs, while other software functions have periodic tasks that are slower or equal to 1 ms.

Building on this foundation, the development team decided to offload the most time-critical simulation computations, such as the inverter model, the synchronous e-machine model, and the position sensor, to the FPGA. These tasks require step sizes in the nanosecond range. In contrast, typical simulation systems operate with step sizes of approximately 1 ms or slower. To maximize acceleration with this concept, it was then decided to migrate the controller functions to the external accelerator as well, since the update rate of

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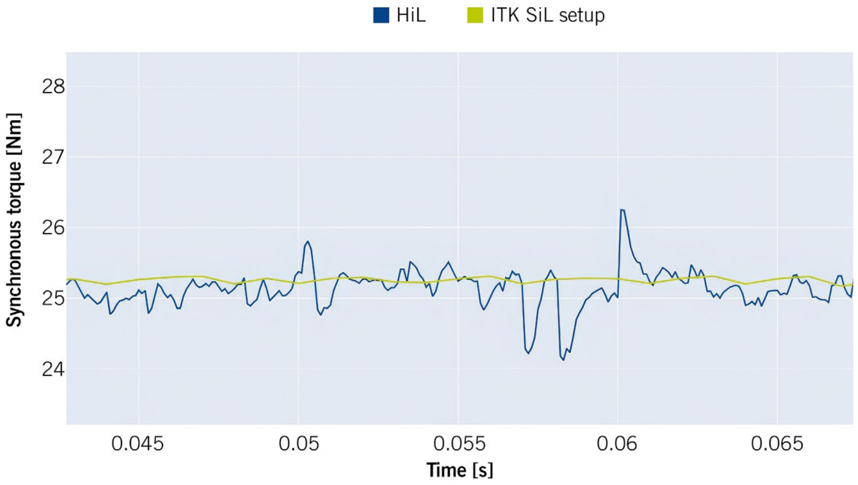

FIGURE 4 Synchronous torque between a HiL and a SiL setup (© ITK Engineering)

the controller output is 10 to 50 times higher than typical simulation cycles. This decision was also influenced by communication latency constraints of around 250 µs.

IMPLEMENTATION OF THE CONCEPT

At the beginning of this innovative project, the cost-effective Kria KR260 board was defined as the local accelerator platform. This board is connected via Ethernet to a local workstation hosting the simulation system. Incoming data is preprocessed by an ARM chip on the board before calculations are performed on the FPGA. The architecture is shown in **FIGURE 2**, within the green frame, including the blue virtual control unit. To extend the setup for system simulation, additional artifacts simply need to be connected to the tool.

To support the concept of reusability, existing, already validated models for safeguarding the inverter verification were transferred from a HiL system to this setup. The models were reused with the help of a Xilinx library for Simulink after modifying their interfaces. As a result, the time required for troubleshooting during the commissioning of this new solution was minimal.

Distributing simulation workloads across different components executed on an accelerator requires a synchronization mechanism. The co-simulation framework running on a CPU acts as the master, while the accelerator operates as the slave. To synchronize the models on the FPGA, the simulation time is used as a reference, and the model is controlled via a counter on the FPGA side. In response to early customer feedback indicating the need for a cloud-capable solution, the development teams migrated the solution to an Amazon F2 instance. The data exchange in this case is handled via a PCIe protocol and improves latency to approximately 1 µs.

SIMULATION RESULTS

To validate the simulation results, the experts followed a three-stage approach. First, they compared the measurements from the accelerated setup with a model-based simulation. This was possible because both the software components and all models could be simulated in Simulink. The scenario involved simulating a constant torque with identical call behavior. The step size for the electrical simulation was 8 ns, while the controller was called every 100 µs. In addition to comparing data, they were able to determine an acceleration factor of over 50,000 between a PC-based and an FPGA-assisted simulation for this use case and using the Silver co-simulation tool in combination with the accelerator, they achieved a real-time factor of 1.4.

In the second validation step, they compared the results from the setup with a stationary measurement taken at a hardware-in-the-loop test bench. For the innovation project, the virtual control unit did not include Microcontroller Abstraction Layer (MCAL)-related software or electrical models of Analog-to-Digital Converters (ADCs). This explains the lower noise in the ITK SiL setup, **FIGURE 4**.

In the final validation step, the teams compared the simulation results with those from an E-machine test bench for several dynamic load step jumps and obtained consistent results, aside from minor electrical noise.

The outputs from the local setup and the AWS environment were identical, confirming simulation consistency across different computing environments. This shows that the acceleration solution is independent of the underlying hardware and can be seamlessly deployed in both local and cloud-based environments without compromising accuracy.

SUMMARY

ITK Engineering is trying to accelerate existing simulators in the automotive industry to obtain design studies, optimizations or test feedback more quickly. Any simulation architecture that supports the FMI standard can potentially be accelerated by this method. Using the example of electric machine simulation, accuracy could be demonstrated in comparison to HiL test benches as well as e-machine test benches. Due to the model-based development approach used for FPGA model implementations, the method can be transferred to other applications with minimal effort. The ability to efficiently distribute computational loads, along with compatibility with cloud environments such as AWS and Azure, further increases the long-term applicability of this approach and paves the way for more efficient and effective simulation practices in the future.

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“Why doesn’t a surface
tell me how it feels?“

SURFACES REIMAGINED.

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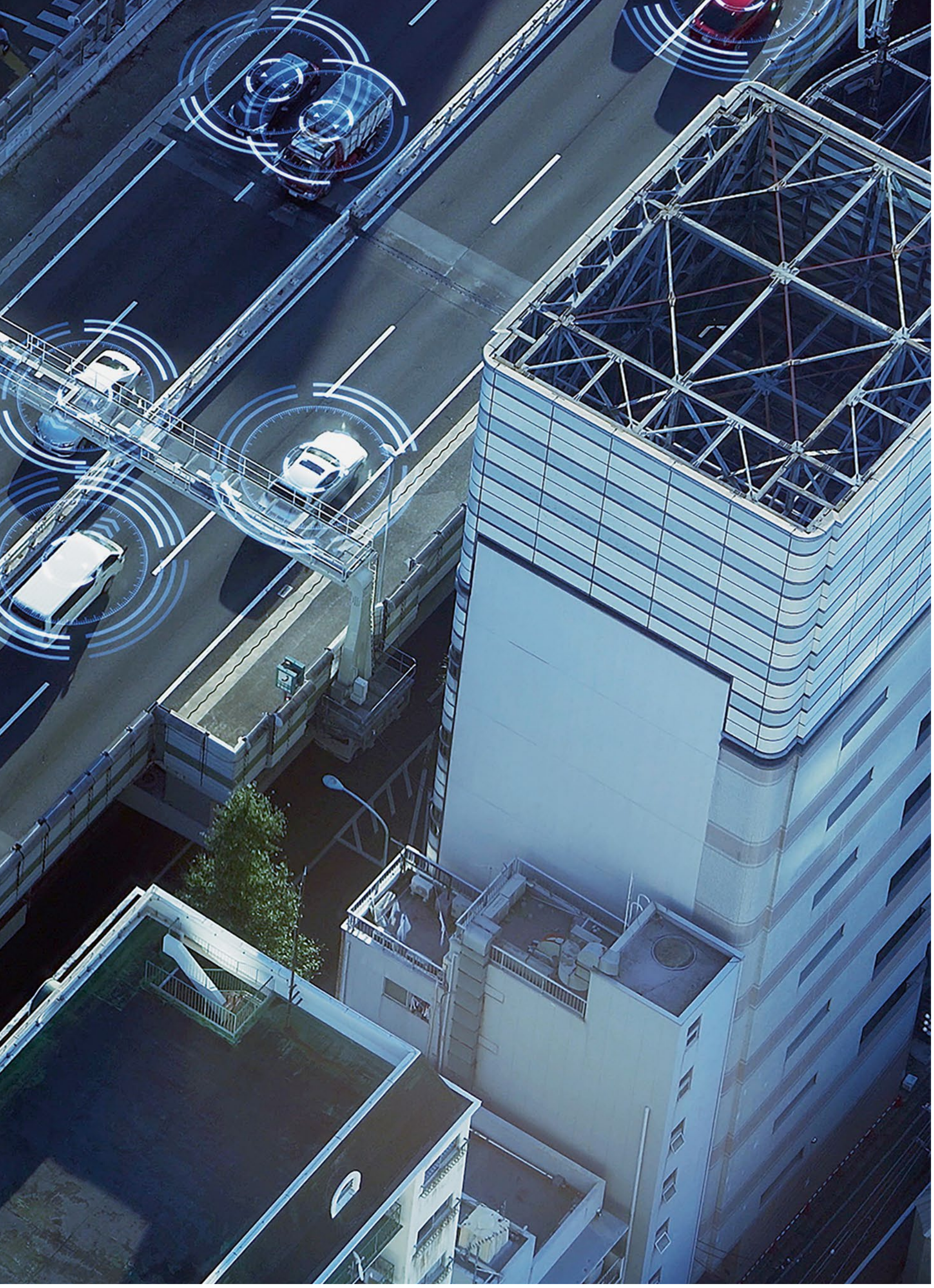
End-to-End Validation System for New Vehicle Generations

The automotive industry is transforming together with its increasingly software-defined product world. In this environment, previous validation and assurance strategies are reaching their limits. ASAP describes in the article a comprehensive end-to-end validation system developed in more than two years, which can verify software requirements in a time- and cost-saving manner.



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WRITTEN BY

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is Project Lead, Software / Virtual Validation with ASAP Group in Ingolstadt (Germany).

In the Software-defined Vehicle (SDV), software and its development and validation process play a central role. In the future, vehicles will be defined much more by their software and its quality than ever before. Both will be crucial in determining whether a vehicle is accepted by customers or not. In contrast, in the traditional vehicle development process, software plays a rather subordinate role. Mechanical components and hardware are defined long before software is developed and integrated. In the SDV, this paradigm no longer applies: Instead, the car is conceived from the software perspective. Software is the main driver of innovation and functionality. Therefore, the development and testing of software must be an integral part of vehicle development from the beginning. New and increasingly complex software, like autonomous driving software, Advanced Driver Assistance Systems (ADAS), connectivity, and Over-the-Air updates (OTA), bring new challenges in the lifecycle of vehicle software. Software must be flexibly adaptable to meet changing environmental and user requirements. At the same time, it is necessary to always ensure the safety and reliability of the vehicle.

OTAs enable software and patches to be made available for the vehicle in almost real-time, allowing for much more frequent adjustments compared to previous updates at dealerships. To cope with these frequent updates, new validation concepts must be developed, especially for safety-critical systems. Therefore, processes and methods such as automation, virtual validation, and traceability in software development and testing are becoming increasingly important.

LIMITS OF EXISTING TEST METHODS

SDVs are characterized by a software-centric architecture and its continuous development throughout the vehicle's lifecycle. This allows developers to integrate new software and functionality

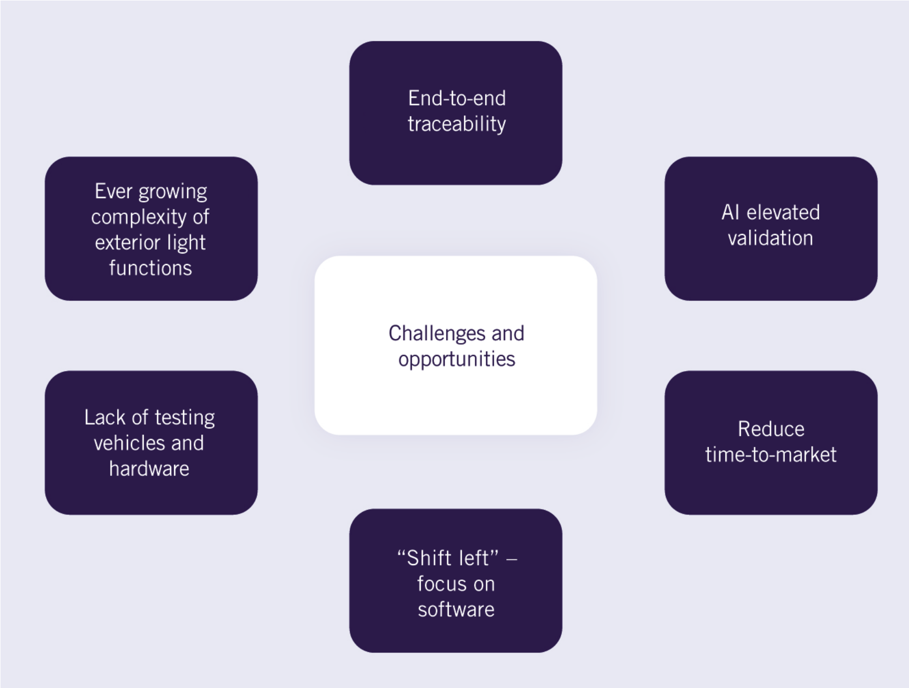
End-to-end traceability
AI elevated validation
Reduce time-to-market
"Shift left" – focus on software
Lack of testing vehicles and hardware
Ever growing complexity of exterior light functions
Challenges and opportunities

FIGURE 1 Previous validation strategies are reaching their limits (© ASAP Group)

via OTA. When these shorter update and release cycles are combined with increasingly complex functions in the vehicle, the result is an exploding number of test cases that must be carried out in ever shorter timeframes [1].

Established test methods, such as Hardware-in-the-Loop (HiL) or vehicle tests, are very suitable for software and hardware validation in principle. However, they scale poorly with a growing number of tests. Although HiL tests enable earlier verification of control units in the development cycle compared to vehicle tests, thus requiring less effort, scalability is limited by hardware resources. Additionally, HiL test benches are maintenance-intensive and require extensive resources such as personnel, space, and energy. To keep the cost and resource requirements in the test process as low as possible, it is essential to shift parts of the validation process into a purely virtual world and closely link it to the development of vehicle software. Software-in-the-loop (SiL) test benches offer a safe and efficient test environment that can be used very early in the software development process. SiL test benches enable the simulation and validation of software components under realistic conditions, without physical prototypes, **FIGURE 1**.

"SHIFT LEFT" WITH TESTSPHERE

To meet the changing requirements of the test process, Testsphere was developed as a comprehensive validation framework that unifies and optimizes test processes. It brings the first test executions closer to the actual development of vehicle functions. Additionally, Testsphere decouples test cases from the test system, allowing the same test cases to be used for SiL, HiL, and even in vehicle tests, **FIGURE 2**. The goal of a unified test designs is, among other things, to improve acceptance and simplify the use of SiL test benches. Ideally, software components are validated in a SiL environment before the first HiL test bench is available. This also applies to any changes to existing software components. The advantages: SiL test benches scale easily and can be used by any software developer to obtain initial release recommendations.

HARMONIZATION OF TOOL LANDSCAPE AND TRACEABILITY

Due to increasingly complex vehicle functions and the associated increase in test executions, reducing manual steps in terms of traceability is essential. Especially in the release process of safety-critical software, the requirements for traceability and revision security are high.

Testsphere supports this process through the central Testsphere editor, which displays all data and information relevant to test case design and establishes links between these and the executed test cases. For example, requirements are linked to software versions and test case revisions. These connections are then synchronized to source tools such as an Application Lifecycle Management (ALM) tool like PTC Codebeamer. Testsphere acts as middleware, ensuring that test reports can always be assigned to software and requirement versions without error-prone manual steps.

One essential feature of the solution is that it enriches existing data with information but does not store it in the Testsphere ecosystem. This can include test cases or test reports. Instead, all data and information are synchronized directly to the target environment, such as the ALM tool Codebeamer, where they are available for further processing and reporting. The Process Automation Kit (PAK), also developed by ASAP, can help as a framework for individual, reusable automations during data migration to an ALM tool like Codebeamer.

ABSTRACTION THROUGH KEYWORD-DRIVEN TESTING

The Keyword-driven Testing (KDT) service integrated into Testsphere according to ISO 2911-5 enables test designers to clearly separate test logic from the test case itself, which is executed on a test system, [2]

By using keywords in the logical test case, three key advantages arise that the solution leverages:

- Abstraction from the actual test system by using keywords when creating test cases to get them created independently of the test system: This facilitates cross-system automation of test case execution. The KDT service implements logical test cases for specific test systems without manual steps
- Standardization of test steps by standardizing them using the definition of simple and composite keywords: This helps to reduce error probability in test case development. Defined keywords can be reused in any test case, making test case creation easier for non-programmers
- Modularity and scalability by using composite keywords enables individual test steps to be grouped together: By reducing test steps, test cases become less complex. Additionally, adjustments and bug fixes can be applied simultaneously to all existing test cases through a single change in the specification of a composite keyword

The KDT framework integrated into the software thus offers a structured and efficient method for creating and managing test cases, allowing the increasing complexity to be broken down into smaller components and making handling easier. In addition to the simplified test design for manual test case creation, the clear structure of KDT also allows for the generation of a basic implementation of the test case using Artificial Intelligence (AI) in the form of a Large Language Model (LLM).

All relevant data for creating a test case, such as requirements, available keywords, or regulatory documents, are provided to the LLM using a Retrieval-augmented Generation (RAG) pipeline and thus added to the prompt context. Testsphere uses an ASAP proprietary Gen AI platform to ensure that customer data is protected and does not leave the ASAP infrastructure. This allows for test case creation tailored directly to the project. Additionally, context-based suggestions for improving test cases and requirements are provided by the AI. The AI integration also enables automated test case analysis and supports developers and test designers through context-based assistance and auto-completion.

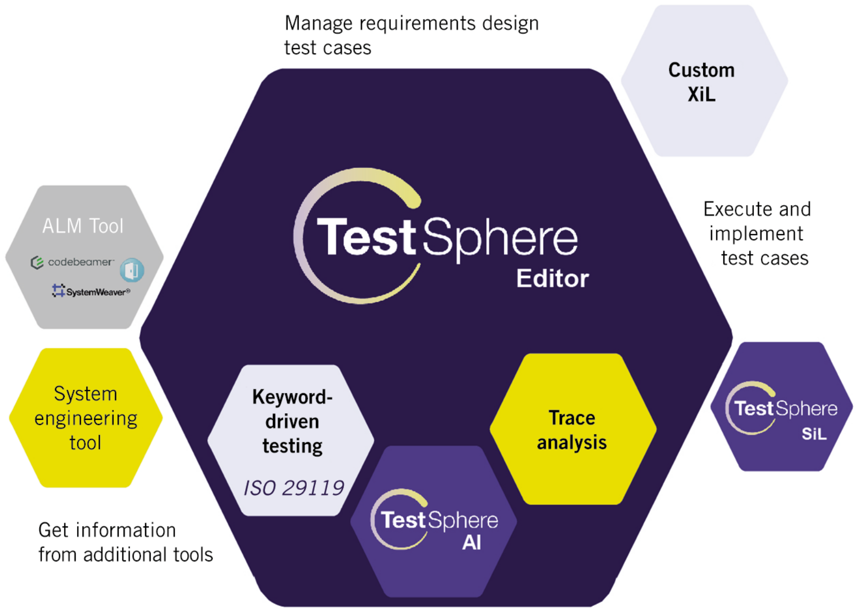

FIGURE 2 Testsphere manages requirements and the test process; various tools can be integrated in this context (© ASAP Group)

GENERALIZED SIL BASIC FRAMEWORK

To enable Testsphere to fully leverage its potential through KDT-based abstraction, various test systems are necessary in the test process. Therefore, the software includes a generic framework for efficient development of a SiL test system. The test system is divided into four central components that are independent of the software being verified. The SIMcore is the main component of the SiL system. It is responsible for environment simulation and can include simulation tools such as CarMaker, Carla, or other models, such as mechanical simulations. Which tools are used in the SIMcore depends on the requirements of the individual software component.

The SIMcore is separated from the virtual Electronic Control Unit (vECU) by the interface provider. The interface provider allows easy exchange of parts or the entire environment simulation without requiring changes to the vECU. The vECU contains the software com-

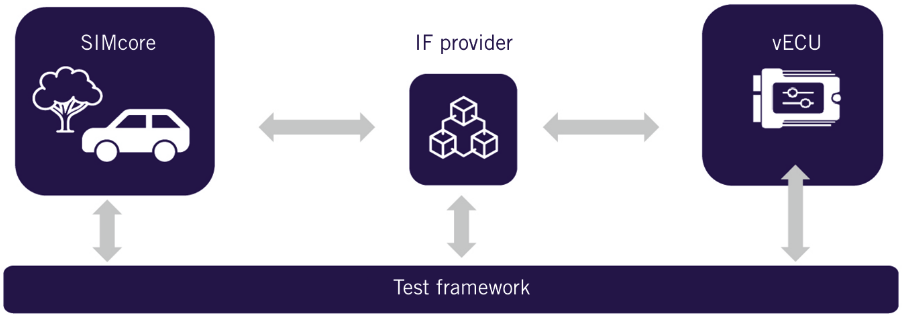

FIGURE 3 The test system is divided into four central components; these are independent of the software being validated (© ASAP Group)

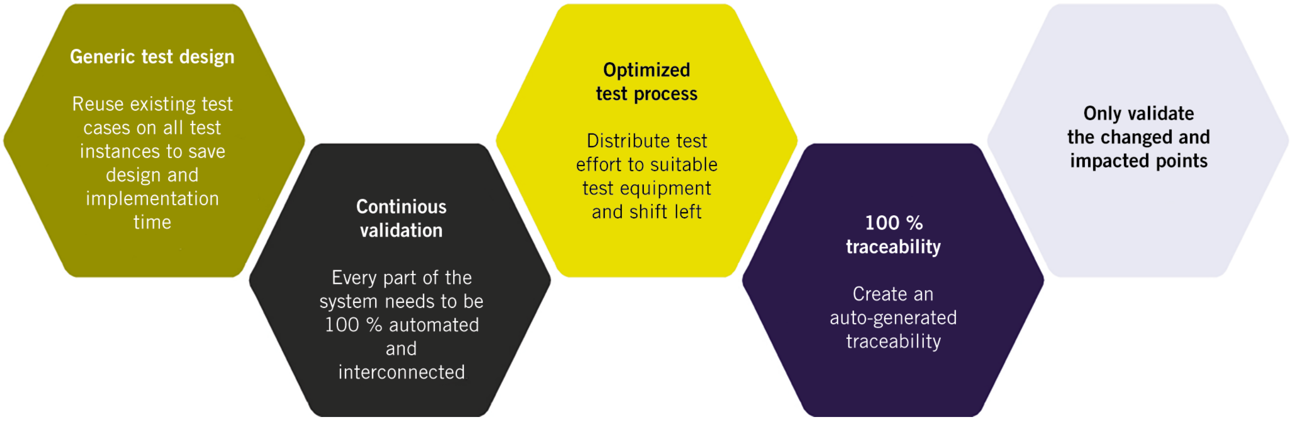
Generic test design
Reuse existing test cases on all test instances to save design and implementation time
Continious validation
Every part of the system needs to be 100 % automated and interconnected
Optimized test process
Distribute test effort to suitable test equipment and shift left
100 % traceability
Create an auto-generated traceability
Only validate the changed and impacted points

FIGURE 4 The basic principle of the system approach is to validate primarily the relevant points that have changed (© ASAP Gruppe)

ponent to be verified. Depending on the test case and target, vECUs from level 1 to level 4 can be integrated. The necessary vehicle bus simulation is integrated into the interface provider and depends on the vECU. For a level-1 vECU, no bus simulation is necessary. From level 2 onward, partial bus simulation is required to validate inter-ECU communication. The test framework forms the interface between the test bench and the test case implementation. It is responsible for executing and evaluating test cases on the SiL test bench and reporting to Testsphere. By clearly defining interfaces between the mentioned components and communication middleware in the SiL basic framework, quick adaptation to any test subjects and environment simulations is possible.

TECHNICAL IMPLEMENTATION

All components of Testsphere are implemented as microservices. These enable the use of components independently of the editor. The exchange of information with tools already used in the test process is established via defined API interfaces. The proprietary tool API is encapsulated by the middleware. The middleware provides a well-defined REST interface through which data from the solution can be read and written. New tools can be efficiently integrated thanks to a REST interface.

The individual components and microservices of Testsphere are delivered as Docker containers, that is, as a standardized, encapsulated environment in which applications are executed. This enables deployment on a variety of systems and is highly scalable. Starting with a local installation on a physical server or on a hyperscaler, that is a high-performance data center like AWS or GCP. The advantage of a scalable infrastructure is that the SiL basic framework can access any number of hardware resources and parallelize test case execution. The web interface of the editor allows the creation and start of test cases independently of the infrastructure.

SUMMARY

With the know-how from a variety of projects, ASAP has developed a test system that unifies the test process across various test systems, achieving comprehensive modularity and scalability in vehicle software validation. This enables seamless integration of test approaches and tools from requirements to release, making the entire process significantly more manageable and cost-effective. Decoupling the test design process from the tool landscape also allows for the adaptation of existing test processes to the challenges in SDV development without having to drop established infrastructure. The heart of the test bench-independent Testsphere is a tool-independent editor that communicates via unified interfaces and connects with the respective ALM tool, system architecture tool, and test system. All data is visualized on a clear user interface, simplifying test design and execution on SiL, HiL, or in the vehicle.

Since the software is a modular system consisting of microservices, the framework will continue to be developed and tailored to customer needs. This includes the integration of new customer-specific or internal tools as well as the expansion of AI functionality. Initially, the focus will be on automated, AI-supported increase in test coverage. The solution targets on embedding maximum flexibility in a variety of different tools and requirements across various test levels into an automated process.

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THANKS

Colleagues from various fields at ASAP are involved in the development of Testsphere. These include: Marcel Fuhrken (Electronics Development), Richard Simon and Markus Laubmeier (EE Test Methodology and Design), Jan Mrochen (Software Development).

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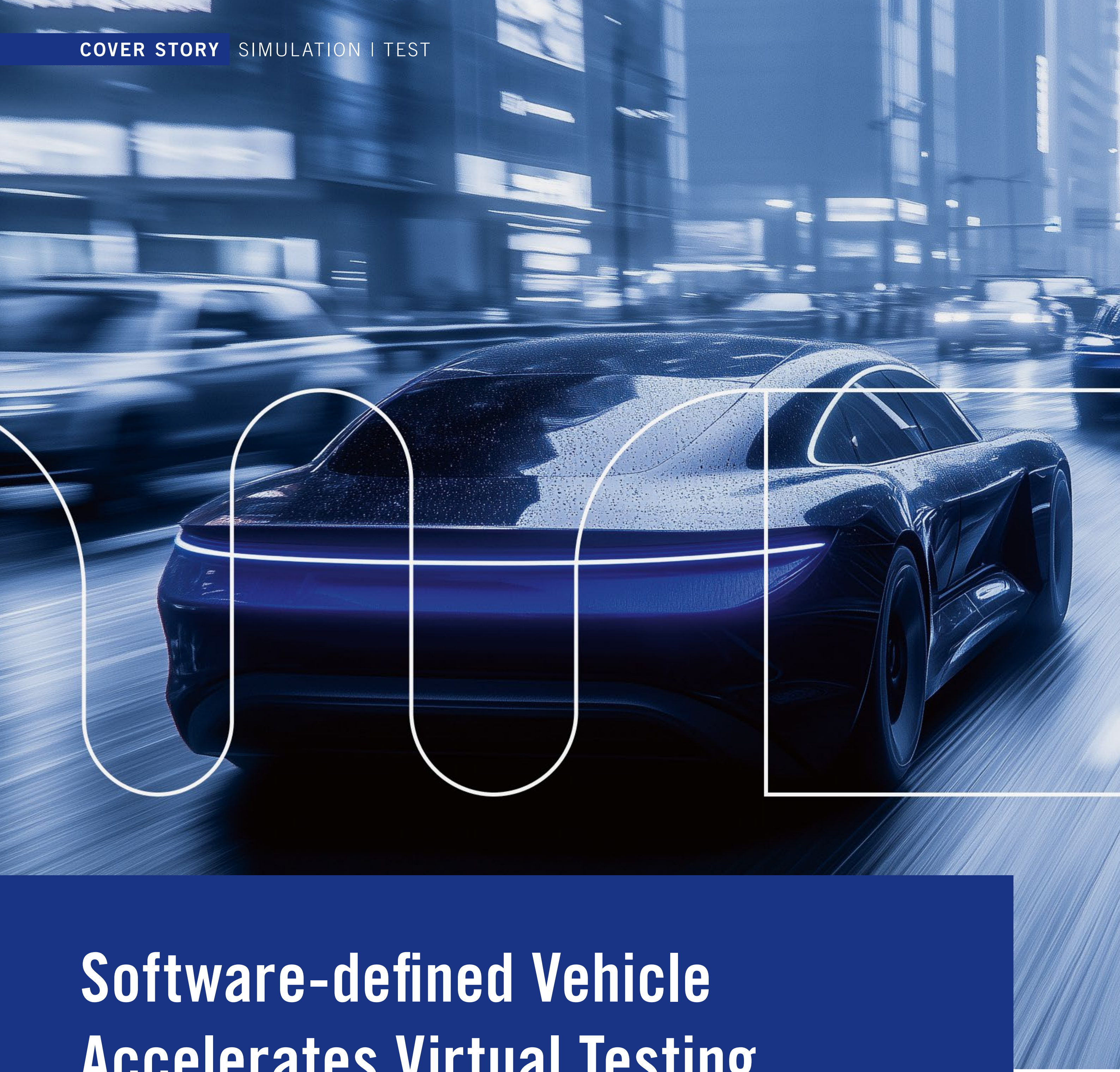

Software-defined Vehicle Accelerates Virtual Testing of ADAS-AD Functions

A software-defined vehicle is characterized by its system architecture, which enables dynamic configuration and supplementation of vehicle functionality without the need for hardware modifications. FEV.io uses an example function for automated driving to show how the advantages of such an architecture can already be exploited during the development process.

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Modern testing methods for Software-defined Vehicles (SDVs) rely heavily on simulation with digital twins to handle larger test volumes and accelerate testing – even in areas previously dominated by vehicle testing, such as homologation [1]. This provides significant benefits for vehicle manufacturers, customers, and government agencies, saving both cost and time and ensuring product compliance and safety throughout the lifecycle of an SDV. In addition to moving tests forward to simulation, an important factor in increasing efficiency is increasing the degree of automation within test processes, including test specification, execution, and evaluation.

Previous studies have shown the automated generation of (scenario-based) test cases from model-based requirements using MBSE or from AI models [2, 3], **FIGURE 1**. Machine-readable test case formats such as ASAM TestSpecification are on the rise and can be used for automatic import and execution of test cases in simulators [4, 5]. Cloud-based simulators are used to parallelize simulations, for example for scenario exploration through parameter variation.

Another great potential for efficiency lies within the functional development phase. An abstraction of the function interface enables the automatable use of the same (possibly containerized) software application on different target platforms, such as a Software-in-the-Loop (SiL) or Hardware-in-the-Loop

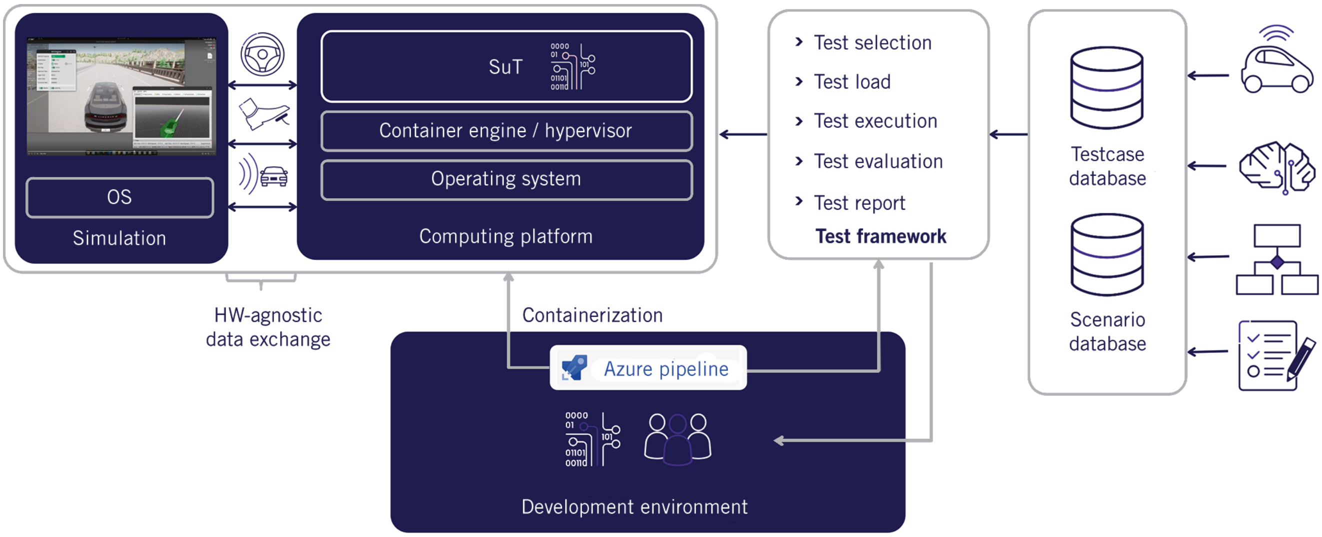

OS
Simulation
SuT
Container engine / hypervisor
Operating system
Computing platform
HW-agnostic data exchange
Containerization
Azure pipeline
Development environment
Test selection
Test load
Test execution
Test evaluation
Test report
Test framework
Testcase database
Scenario database

FIGURE 1 Test framework with abstracted function interface (© FEV.io)

(HiL) environment, or directly in the vehicle, **FIGURE 1**. When new software code is released, the application is built automatically and distributed to the target test platform. The application to be tested becomes the System-under-Test (SuT) there. A traffic and vehicle simulation is controlled via test cases and scenarios and provides virtual sensor data as it would occur in the physical vehicle.

Test control and evaluation are handled by a suitable test framework, which loads the test cases and scenarios from the databases, controls the test execution and prepares the results for test evaluation. The test cases and scenarios can be generated from the functional specification [2], but also from test drives or regulatory requirements. In the future, AI-supported generation of test cases and scenarios is also expected to play a significant role [3].

SDV ARCHITECTURE ACCELERATES DEVELOPMENT

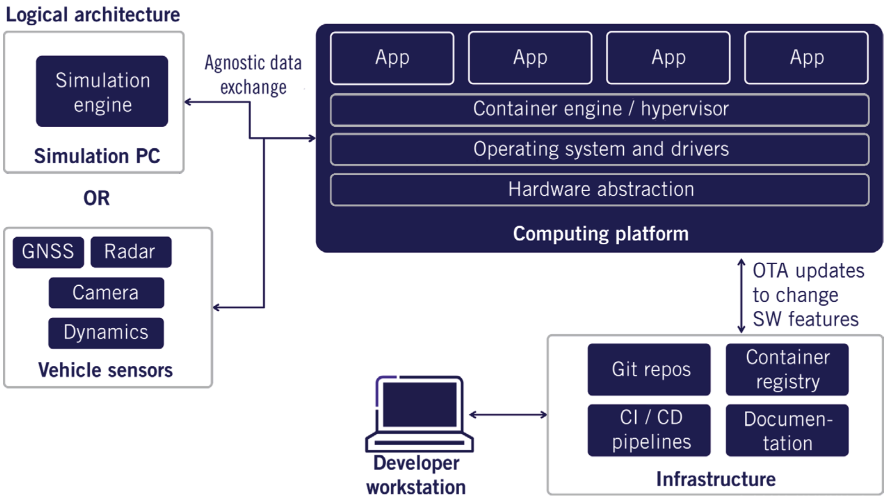
Probably the most important feature of an SDV architecture is the separation of hardware and software because this decoupling – ideally the elimination of dependencies between the software and the hardware used – enables the driving forces behind SDV: personalization, adaptability, automation, and service-oriented business models. This article will highlight the benefits that can already be utilized in the software development phase.

On the one hand, the independence from the underlying hardware makes it possible to use and test the same application as SuT in both the vehicle and in a SiL environment. The hardware interface remains identical for the application in both cases, as it is hardware-agnostic. In the first case, the sensor data comes from a specific vehicle and in the latter from a simulation, which runs a virtual vehicle and scenarios and which generates the corresponding data, **FIGURE 2**. On the other hand, software functions in a SDV architecture are often encapsulated via containers and can thus sometimes even be replaced during operation. The distribution of such containers to a system can be easily automated, and this automation in turn enables incremental and iterative feature development through continuous integration and testing the SuT on function level (CI/CD). Project risks that arise from very late function tests in the vehicle can thus be significantly reduced.

FOCUS ON THE TARGET CODE

The logical architecture shown in **FIGURE 2** has been implemented as the concrete architecture in **FIGURE 3**. Its aim is to be able to continuously test a software vehicle function to support the development phase with fast

FIGURE 2 The logical modules of an SDV-based development and test environment (© FEV.io)


Logical architecture
Simulation engine
Simulation PC
OR
GNSS
Radar
Camera
Dynamics
Vehicle sensors
Agnostic data exchange
App
App
App
App
Container engine / hypervisor
Operating system and drivers
Hardware abstraction
Computing platform
OTA updates to change SW features
Git repos
Container registry
CI / CD pipelines
Documentation
Infrastructure
Developer workstation

feedback cycles and to permanently monitor the quality of the overall system. The architecture should also enable a workflow that is as independent as possible from the target system. The system components are grouped in Preparation, Execution, Reporting, as well as Scenario and Test-Case Databases.

The tools in the preparation box, **FIGURE 3**, collect and build the artifacts needed in the execution. The test scope is determined here and is based, among other things, on the policies of a Git workflow, which is the rules that are defined by Git branch. For example, daily commits on a team branch trigger a smaller amount of testing than less frequent releases on a release branch. The central organizational entity is the pipeline, which automates the necessary work steps.

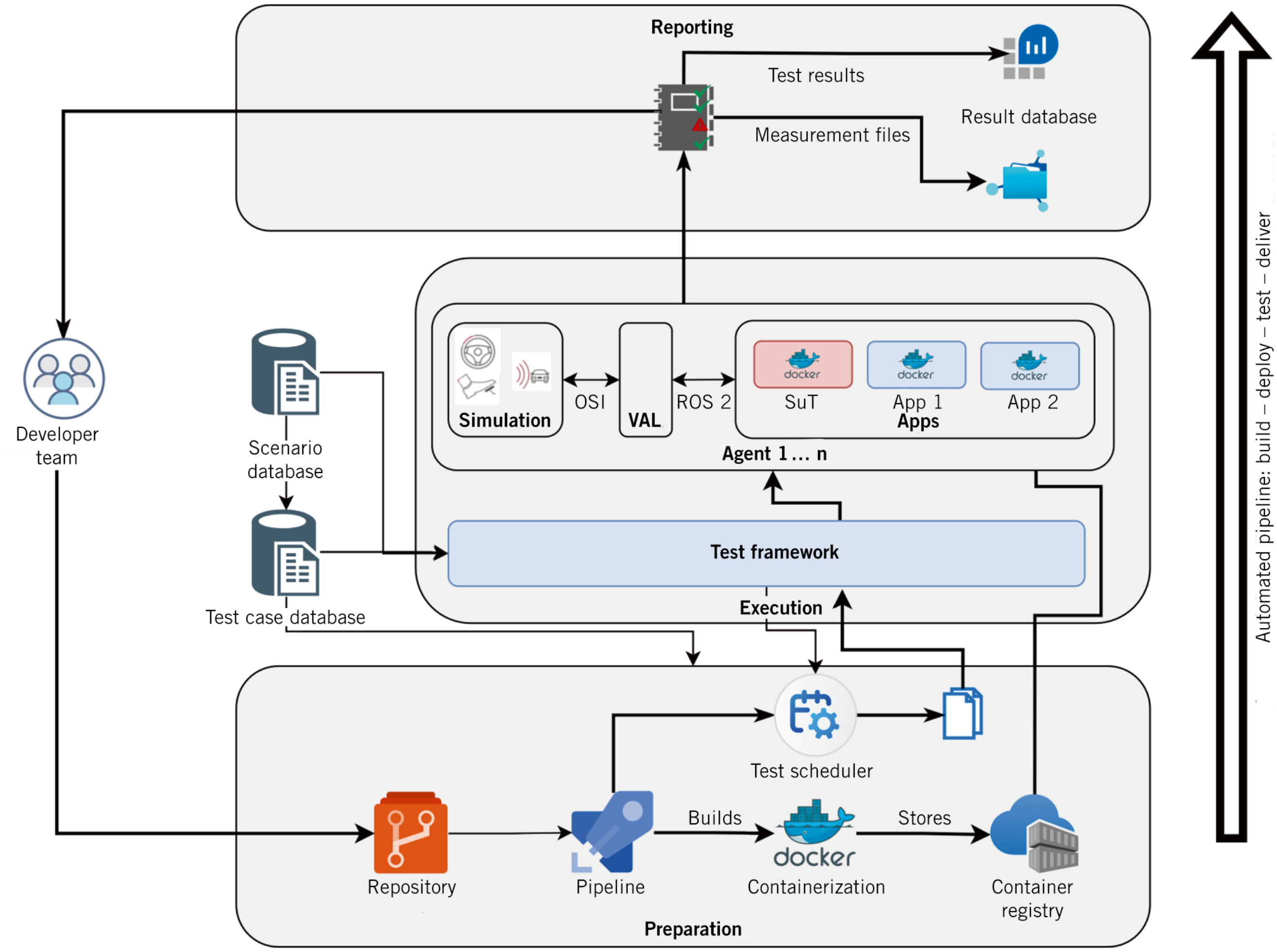
These include building the application from the source code, encapsulating the application in a container, or storing it in a container registry for later use in execution. In addition, the target system (SiL, HiL, or vehicle) and the test scope (for example through Git workflow rules or manual specifications) are defined. The latter determines the test cases and scenarios to be executed. Finally, the test instructions are transferred to the test scheduler.

The execution of the tests is controlled and monitored by a framework. The scheduler determines the scope and execution time, and the appropriate cases and scenarios are loaded from the databases for execution. Depending on the scope, the test framework launches one or more agents. Each agent, in turn, starts a simulation environment and the SuT together with other required apps as docker containers.

The Vehicle Abstraction Layer (VAL) was implemented by a ROS 2 node and the interface to the simulator was implemented according to the ASAM Open Simulation Interface (OSI) standard [6]. This implementation basically enables the connection of any OSI-compliant simulation environment. The VAL takes care of the translation and conversion of data formats. For example, the sensor data supplied by OSI is unpacked and converted, if necessary, for example for unit conversion. The processed data is then packaged in ROS 2 messages and sent to the SDV page or apps, **FIGURE 4**.

Reporting evaluates the pass/fail criteria for all test cases and stores the results in the results database. Since the introduction of a VAL means that the applications (including the SuT) use their interfaces regardless of the target system, the visualization of the test report can be presented generically.

FIGURE 3 Automated SiL simulation architecture for SDV software (© FEV.io)


Reporting
Test results
Result database
Measurement files
Developer team
Scenario database
Test case database
Simulation
OSI
VAL
ROS 2
docker
SuT
docker
App 1
Apps
docker
App 2
Agent 1 … n
Test framework
Execution
Test scheduler
Repository
Pipeline
Builds
docker
Containerization
Stores
Container registry
Preparation
Automated pipeline: build – deploy – test – deliver

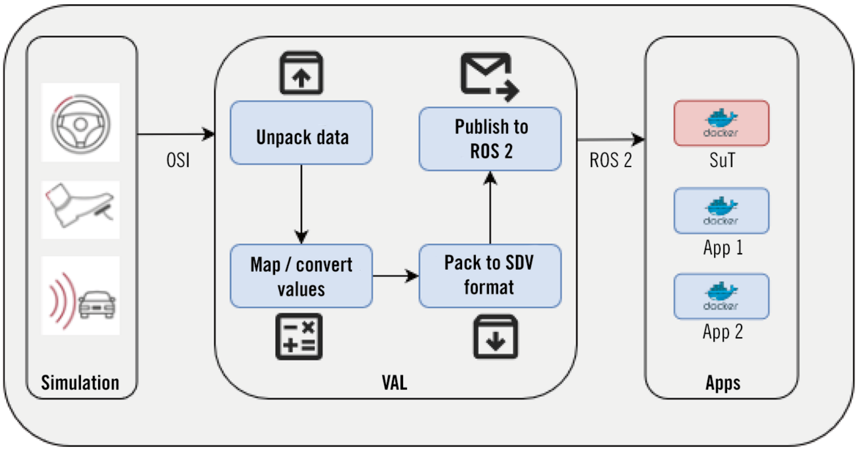


FIGURE 4 Structure of the Vehicle Abstraction Layer (VAL) (© FEV.io)

For quick evaluation, the current test result is compared with the last result and saved as a difference file.

The test case database stores automatable test cases in an XML data format [5]. Each test case refers to one or more scenarios that are stored in the OpenScenario XML Format (OSC XML) in the scenario database. In addition, each test case contains the pass/fail criteria for later automated evaluation.

DEVELOPMENT ITERATION FOR CONNECTED ADAS DRIVING FUNCTION

As part of the HiDrive project [7], a highly automated driving function for entering a highway was developed at FEV.io. In preparation, the scenario, the requirements and the architecture specifications were implemented in Systems Modeling Language (SysML). From this, machine-readable test scenarios and test cases were derived with the help of automated export functions and stored in the databases [2, 5].

As part of an exemplary development iteration for the driving function the development team pushes new code into a central Azure DevOps repository. This event starts an Azure pipeline that uilds a docker container from the application and stores it as an object to be tested (SuT) in a container registry. The pipeline selects relevant test cases based on the branch rules and adds the tests to the simulation queue of the test scheduler, referring to the SuT of the container registry. The test framework launches one or more agents with the simulation environment and the configured VAL. It then starts the SuT as well as other apps as docker containers. The test framework executes test cases according to the scheduler's specifications and stores measurement data including metadata for reporting. The team evaluates the result based on the report and the visualization and can identify and analyze conspicuous test cases via the difference file.

SUMMARY

This article shows a test system that can leverage the advantages of an SDV architecture already in the development phase of vehicle functions. A CI/CD pipeline automates the work steps and controls both the test scope and the testing on the respective target platforms (SiL, HiL or vehicle). A workflow is outlined, which triggers a scenario-based test suite for each functional increment.

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THE HANSEN REPORT
ON AUTOMOTIVE ELECTRONICS

Editorial Notes

Dear Reader,

Donald Trump's crackpot automotive tariffs will put the brakes on innovation. The tariffs will make new cars even less affordable than they already are, putting them beyond most people's budgets.

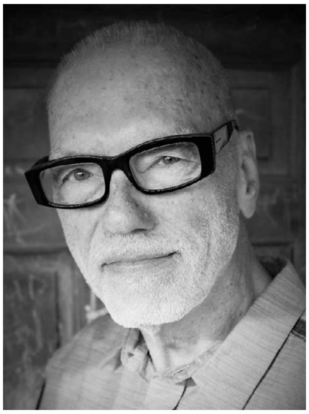
Carmaker revenues and profits will decline and so will their R&D spendings. New, centralized architectures will be delayed. Software-defined vehicles will be delayed. AI applications will be delayed. Electric vehicles will be delayed. Funding for innovative startups will be delayed.

The advanced technology that's already embedded in high-end vehicles will take longer to trickle down to mass market brands. All while China continues to make cars safer, less polluting, more autonomous, and more affordable.

Respectfully,

Paul Hansen

Paul Hansen
Editor



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Software-enhanced Radar

Since its founding in 2017, Zendar has been advancing the performance of automotive radar technology with software. Supported by investments from NXP and Silicon Valley venture capital companies, the firm is offering two radar technologies that will make Automated Driver Assistance Systems (ADAS) safer and more capable: Distributed Aperture Radar (DAR) and AI-enhanced radar software. DAR vastly improves resolution and accuracy by fusing the output of two or three standard, low-cost radar sensors. AI-enhanced radar software can be downloaded to radar-equipped vehicles already in the field, allowing automatic emergency braking to work at higher speeds. The company is not stopping there. It provocatively asserts that its radar-centric approach to ADAS could upend camera as the dominant sensor technology in ADAS.

Semantic Spectrum AI Radar Perception

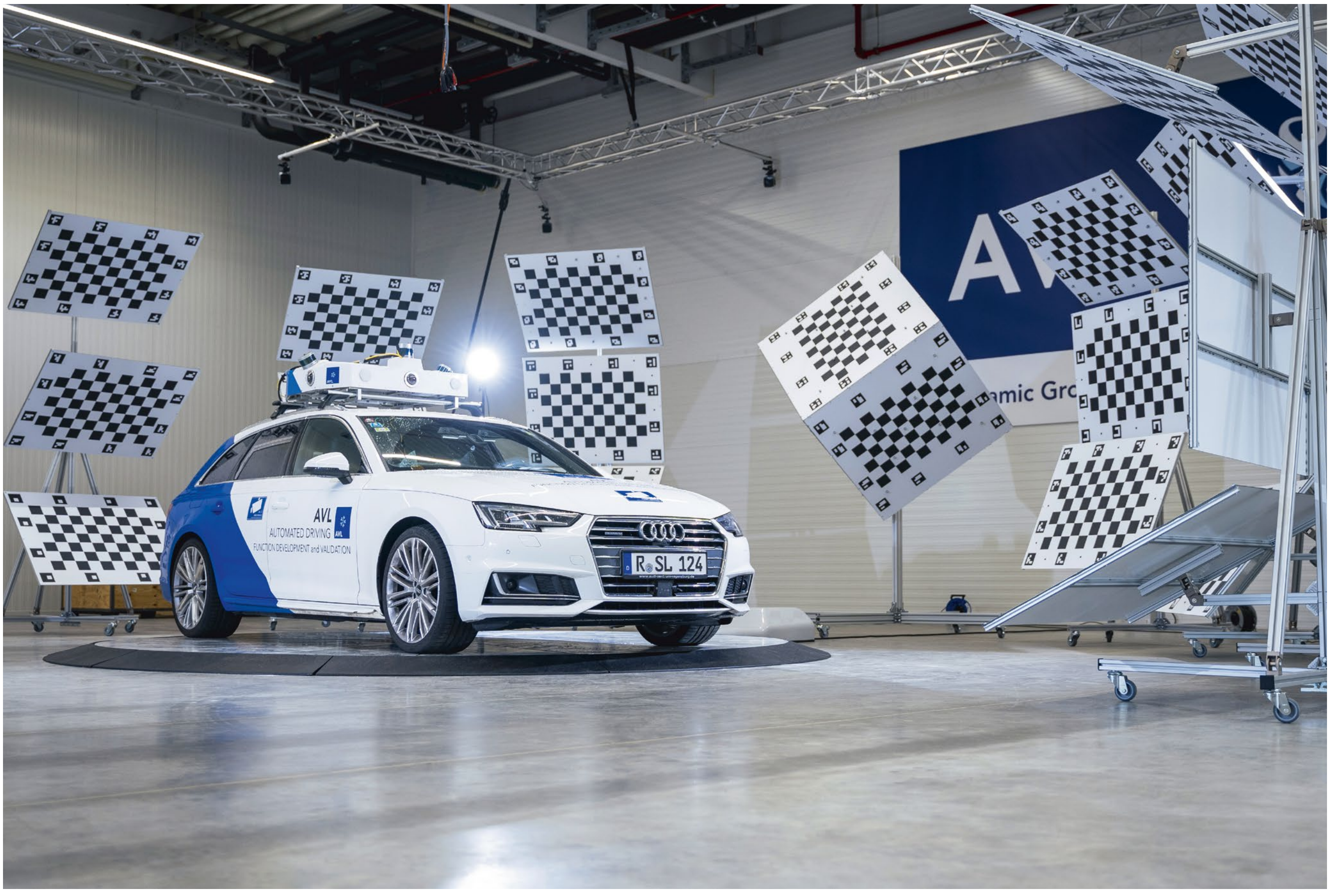
"We're translating raw spectrum data through a neural network to give us a semantic understanding of the world – where the objects are, how big they are, what they are doing," said Zach Beasley, Senior Manager of Marketing and Business Development at Zendar. Instead of the usual approach that requires a lot of processing of the raw data to arrive at a point cloud, their AI radar turns raw radar data directly into a precise understanding of the scene. "We can detect cars at a long distance, whether they're moving or stationary, because we have a radar signature of what a car looks like and what a bridge looks like in the radar spectrum."

In the United States, the automatic emergency braking regulation FMVSS 127 bolsters the demand for Zendar's AI-radar solution. By September 2029, the standard requires all cars to be able to stop and avoid contact with a vehicle in front of them from speeds up to 62 mph (100 km/h). It further requires that the vehicle applies the brakes automatically at speeds up to 90 mph (145 km/h) when a collision with a lead vehicle is imminent, and up to 45 mph (72 km/h) when a pedestrian is detected.

According to Beasley, NHTSA originally estimated that the mandate would add just 25 US dollars to the OEM's per vehicle cost. Lidar or an infrared camera would cost way more than that. "AI radar allows you to fulfill the mandate's requirement with a standard 4 × 4 sensor [four transmit and four receive channels]. All you will need is a software update." Revenues from Zendar's AI radar are expected to begin in 2028 and ramp up in 2029.

Distributed Aperture Radar

In order to offer autonomous highway driving at higher speeds, OEMs need a sensor with more range and more accuracy. They like radar because it is not limited by bad weather or poor lighting. But more resolution is needed. When traveling fast, cars need to be able to distinguish stationary vehicles from bridges, notice a pedestrian changing a tire in the breakdown lane, and accurately localize road debris – all from 300 or more meters



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Automated driving functions at Level 3 and above require complex testing, not least of the sensor technology away. High-resolution imaging radar sensors are being developed by adding more transmit and receive channels, but that increases the demand for power to transmit and process the radar signals. Increasing the size of the aperture would improve resolution, but the size of the aperture is limited by the need to integrate the sensor with the front of the vehicle.

Instead of relying on expensive advances in hardware, Zendar has developed software that fuses the output from standard mid-range radar sensors into a single antenna array that is coherent. DAR is essentially very accurate, long-range imaging radar that is cost-effective, they say. A three-sensor array would cost about 75 US dollars plus the cost of the compute engine that fuses the data stream from each radar. “That could be done by the central compute that’s already in the car or with a small lightweight ECU such as the Purple Box, a reference design from NXP,” suggested Beasley. Zendar’s DAR solution competes with high-end imaging radar offerings from Arbe, Mobileye and Continental, which cost anywhere from 120 to 500 US dollars each, he estimated. “Other companies are developing DAR solutions, but Zendar’s is the only solution that is commercially available,” he asserted.

NXP, which claims to be the world’s top radar-chip supplier, has been investing in the firm and collaborating with them on DAR development since November 2023. Zendar has also worked with Texas Instruments and says its software can run on high-performance computers from Nvidia and Qualcomm. The company’s revenues from DAR L3 highway self-driving applications are expected to begin in 2030.

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0.25°
AZIMUTH RESOLUTION
1.0°
ELEVATION RESOLUTION

DAR is Zendar’s newest AI-supported, high-resolution radar-centric approach to ADAS

Radar-Centric ADAS

Zendar believes that radar can do the work of ADAS more efficiently than can cameras, including object classification, detection of static and moving objects, and object velocity. Today, cameras are the bedrock of ADAS, but unlike radar, they don’t provide native 3-D intelligence.

“You need much less data to train an AI-radar model than to train a camera-AI model,” said Beasley. “With a radar-centric approach to ADAS you still need a camera for things like lane markings, traffic signs and signal lights, but you can reduce the amount of work the processing has to do and save money on the compute.” Compute is the biggest ADAS cost driver. Radar-centric ADAS would deliver big cost savings. It needs a compute stack capable of performing just 10 TOPS (trillion operations per second) compared with 200+ TOPS for camera-centric ADAS. Over the next few years Zendar will determine if its radar-centric approach can also be applied to full self-driving. With 65 employees currently, and scaling up to about 150 employees by 2028, the company will soon enter its series D funding round. Revenues are negligible but will begin to ramp up in 2028.

Siemens | Nvidia | GM | Yazaki | Roland Berger | Sumitomo

E/E Trends Update with Doug Burcicki

Doug Burcicki is Senior Director of the Integrated Electrical Systems Global Automotive team at Siemens Digital Industries Software. He is responsible for three product lines, including the E/E system computer-aided architecture optimization tool called Capital. Siemens’ Capital plays a pivotal role in the design, engineering and manufacturing of automotive wiring harnesses. Burcicki recently completed a series of discussions with wiring harness suppliers and tier 0.5 vehicle integrators. We spoke with him about the state of wiring harness business and technology, about the prospects for mass production, the rise of complexity, and about tariffs.

While today a lot is happening on the frontiers of automotive electronics, change comes very slowly to the wiring harness industry.

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Doug Burcicki has been with Siemens Digital Industries Software for seven years. Before that he spent 25 years at the wiring harness manufacturer Yazaki, where he held increasingly responsible roles in engineering and business management

"The feedback I'm getting from the companies that assemble wiring harnesses is that very little has changed in the last 80 years," noted Burcicki. "Some new technologies are creeping in, but nothing that's earth shattering. The plan has aways been, build wiring harnesses as cheaply as possible, which means you build them in far-flung regions of the world where the cost of labor is low, and then you ship them around the world."

Automation

Wiring harness manufacturing continues to be exceedingly labor intensive. "Labor accounts for 30 % of the finished goods cost of the wiring harness," said Burcicki. "BOM [bill of materials] is the next biggest cost. … Every major wiring harness company claims to automate wiring-harness manufacturing, but they only mass-produce small harnesses, like a door or engine harness, not large harnesses." The main obstacle to automated wire harness production is the lack of standardization. Carmakers provide a wide range of optional features for each model, leading to exponential growth in the number of wiring-harness variations.

There are several projects underway to advance the automation of wire harness manufacturing within the far-reaching ARENA2036 initiative in Germany. The DIN 72036 standard includes practical guidelines to make wire harness production more efficient. The standard is being extended to high voltage and high frequency wiring. "ARENA2036 is making progress, and the number of contributing members has grown," said Burcicki. "It will enable some automation in Germany and elsewhere," he said, adding "How much of the harness gets automated will depend on the scale of the adoption of new SDV architectures that lead to simplified wire harness assemblies. The broad adoption of ADAS features in developed markets could lead to the further adoption of small, modular wiring harness assemblies that can be automated."

Nvidia has suggested that carmakers should equip every vehicle with enough hardware to support automated driving. Automated highway, and eventually urban driving could be implemented post-sale via software downloads paid for with subscriptions. "Nvidia's model assumes that carmakers want to give hardware away to make money later on software. We don't yet know if enough consumers will be willing to the make the monthly payments necessary to have the car drive itself during certain portions of their commute," said Burcicki. "More automated wire harness production is coming, but I don't see automated driving as a game changer in the automation of wire harness production," he concluded.

Complexity

Electrical system variance is exploding. Burcicki: "Wiring doesn't get a lot of respect, but it's one of the most challenging aspects of automotive engineering. The reason is complexity. A high-line GM vehicle has millions of customer-specific wiring harness combinations. A company like Yazaki has to be able to design, validate, track and have components for all of those configurations."

The world's best wiring harness companies are able to handle complexity anywhere in the world and do so profitably. "One of the worst kept secrets is that every design change that comes in from the carmaker brings profits to the harness maker," Burcicki said. "That's how they make their money. They don't really want scalable modular architectures that you can automate and run in a plant overnight with the lights out. That's the end of the industry for them."

Regionalization

Despite its unvarying past, the wiring harness industry is becoming unsettled. The tariff war is accelerating trends that were already beginning to transform the automotive supply chain. Last fall Roland Berger began discussing "polarization" in the automotive supply industry as part of their Automotive Outlook 2040 analysis: "The automotive industry is shifting from globalization to regionalization. Geopolitical tensions and diverse regulations are driving localized supply chains. Suppliers must adapt to regional preferences and market dynamics such as China's dominance in EVs."

"Over the next 20 years the wiring industry will go through profound changes," Burcicki ventured. "No matter what happens with tariffs, OEMs are reevaluating their sourcing strategies around components and wiring harnesses." Instead of sourcing wiring harnesses globally from suppliers like Yazaki or Sumitomo and shipping them all over the world, OEMs will source them locally in regions where they are building cars. "The tariffs and the breakdown in global trade is going to upend the wiring harness business model," he predicted.

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Top News of the Month |
ZF Receives Approval for Level 4 System

ZF is allowed to test a level 4 system for autonomous driving on public roads throughout Germany. The approval covers urban and regional local transport areas.

Link to the related article:
www.springerprofessional.de/en/link/50830734

AD ACTIVE
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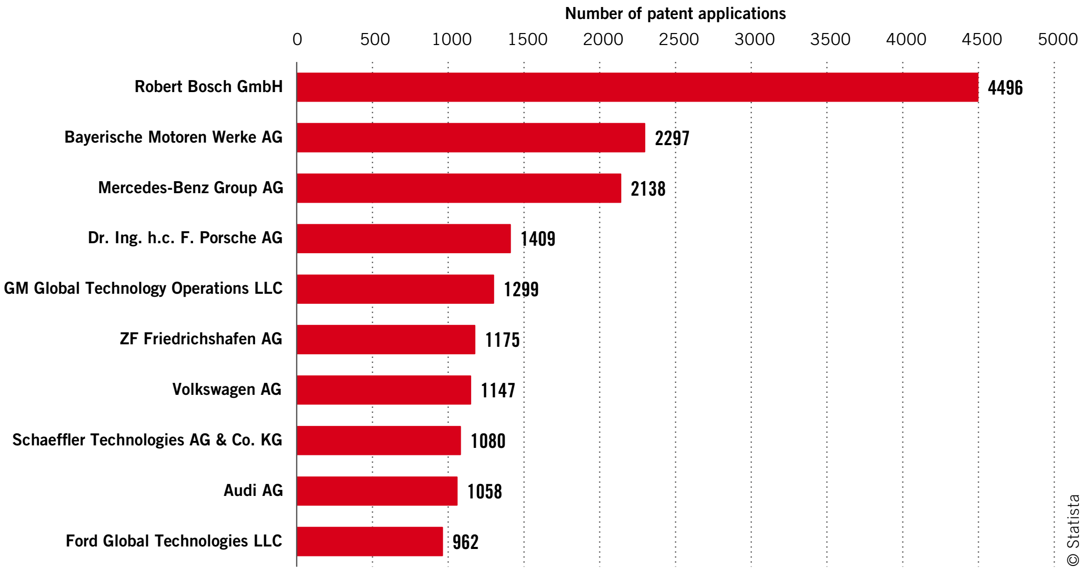
Infographic of the Month | **Automotive Industry Dominates Patent Ranking**

Companies with the most patent applications filed with the German patent and trademark office in 2024



Note(s): Germany excluding any affiliated companies.
Source(s): DPMA; ID 258128

The annual statistics of the German Patent and Trademark Office for 2024 show that the Top 10 of the patent ranking are exclusively occupied by automotive manufacturers and suppliers.

Link to the related article:
www.springerprofessional.de/en/link/51001054

Review | **How the BYD Seal U DM-i Performed in Testing**

The Chinese car brand BYD is best known for its battery-powered electric vehicles. The Seal U DM-i expands the range with a PHEV SUV.

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In the Spotlight |
Tesla and BYD Batteries Compared

To date, there has been very little detailed data and analysis available on modern batteries for electric cars. Researchers at RWTH Aachen University have now dismantled and compared the latest traction batteries from Tesla and BYD.

Link to the related article:
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IMPULSES

Dr. Alexander Heintzel
Editor in Chief
ATZ | MTZ | ATZelectronics |
ATZheavyduty

Acting Consistently

In order to shape a sustainable and climate-friendly future for mobility, three areas of action must be considered in the transport sector. Firstly, forward-looking planning of energy generation and supply, as well as the consistent development of efficient drive systems. From this perspective, in addition to the market introduction of alternative, sustainable fuels and the indispensable storage of electricity from sustainable sources in electrons or molecules, the power electronics required for intelligent charging and driving also play a role.

Second, vehicles must be developed more holistically than ever before in order to meet the necessary requirements in tough everyday operation. Here, too, powerful, robust electronics are essential, and the software-defined vehicle is an important step in this direction. And third, automated driving at levels 4 and 5 can play a decisive role in helping vehicles operate at their optimum operating point. However, private transport will not be the major driver here driver, as it is likely to remain at level 2++ in the near future.

Public transportation is much more likely to be the major enabler of this progress, as it will make this step possible in the medium term. Both urban and rural areas are seeing automated shuttle and bus-on-demand concepts that are on the verge of becoming permanent fixtures. It is important to act consistently now and quickly identify projects in order to create the necessary synergies between public, private, and commercial transport.

ChargePoint | Eaton | Partnership in EV Charging

ChargePoint and Eaton have agreed to partner to accelerate and simplify the expansion of electric vehicle charging infrastructure in the US, Canada, and Europe. The companies will integrate charging and infrastructure solutions and jointly develop new technologies to advance bidirectional power flow and V2X capabilities. As a one-stop shop solution for the charging ecosystem, charging and electric infrastructure and engineering services will be provided as turnkey offerings for electrification – from vehicles to charging stations to power grids.

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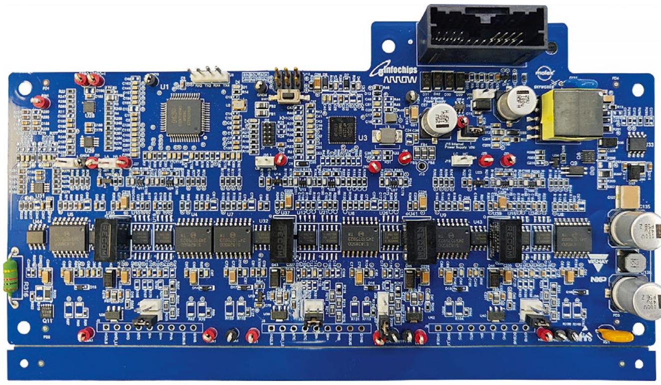
Phytec | EVCS Cube Consortium Founded

Phytec, Pionix, Frickly Systems, CuroCon, and Alp have agreed to collaborate in the field of charging technology for electric vehicles and to found the EVCS Cube Consortium. The EVCS Cube is a development kit for DC and AC charging solutions that was created in a joint project and will be further developed. The basis is the modular phyVERSO-EVCS charge controller from consortium leader Phytec. Pionix provides the BaseCamp Charger operating system, Frickly Systems is responsible for driver adaptation and system integration of the components, and Alp is responsible for developing the housing. CuroCon provides support in the design of the components through to testing of the overall system.

Arrow | eInfochips | Vishay | Reference Design for Traction Converters

Arrow Electronics and eInfochips, in collaboration with Vishay eMobility, have developed a reference design for low-voltage traction converters for light electric vehicles. It is suitable for e-bikes and e-scooters, as well as compact commercial vehicles and agricultural vehicles. The design is based on NXP's S32K3xx MCU platform and a power board from Vishay, offering a complete hardware and embedded software solution with support for functional safety and pre-compliance with IEC61508 standards. The modular and scalable architecture is optimized for 48-, 72-, and 96-V applications and supports power ratings up to 3 kW.



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Asahi Kasei | Dirac | Partnership Agreed

AKM
AK7709VQ
2230EZE

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Asahi Kasei Microdevices (AKM) and Swedish digital audio provider Dirac have announced a partnership to integrate Dirac's AudioIQ acoustic solution into AKM's digital signal processors for the automotive sector, including the AK7709. The partnership will enable AKM to embed Dirac's proprietary algorithms into its next generation of audio DSPs. As outlined in Asahi Kasei's fifth global vehicle user study in 2023, passengers will place increasing value on the in-cabin experience as vehicles become more autonomous. Together, the two companies aim to meet the growing demand for immersive in-car entertainment while addressing OEMs' challenges with laborious tuning processes. This will enable automakers to deliver world-class sound performance that adapts to any interior configuration.

AT&S | **IC Substrate Plant and Competence Center**

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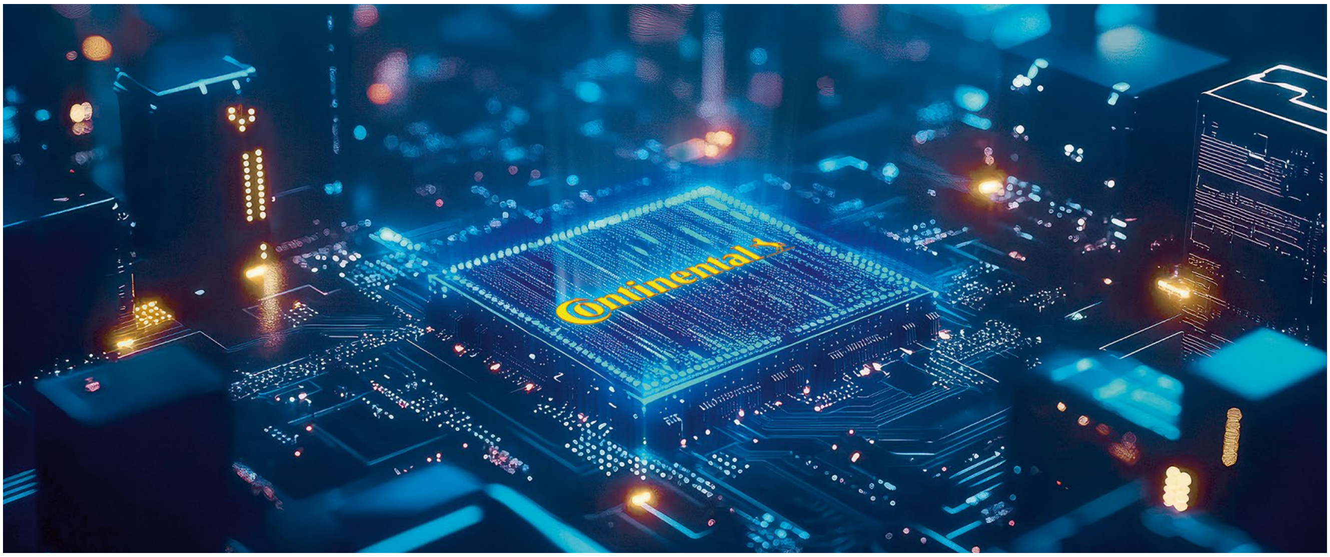
After three years of construction, AT&S has opened a new competence center for the development and production of IC substrates in Leoben. The new Hinterberg 3 (HTB3) complex already employs 420 new employees. This completes AT&S's global research and production triangle for highly developed IC substrates, which also includes sites in Malaysia and China. With HTB3, Europe now has its own capacity for researching and producing IC substrates for the first time. The plant was funded as part of the IPCEI program, which aims to promote European research in the field of microelectronics.

Continental | **Dedicated Organization for Electronics and Semiconductor Solutions**

As part of its spin-off as an independent company, Aumovio, Continental's Automotive division has established a new unit for Advanced Electronics & Semiconductor Solutions (AESS). The company aims to strengthen its resilience and lay the foundation for sustainable success. The organization will develop and verify semiconductors for the automotive industry, primarily to meet internal demand. GlobalFoundries (GF) has been selected as the strategic manufacturing partner, where a production line will be set up to manufacture semiconductors exclusively for Continental Automotive. AESS will not only enable the establishment of a resilient supply chain but also increase product quality and shorten time to market. In addition, the organization offers the potential for value creation through savings and efficiency gains.



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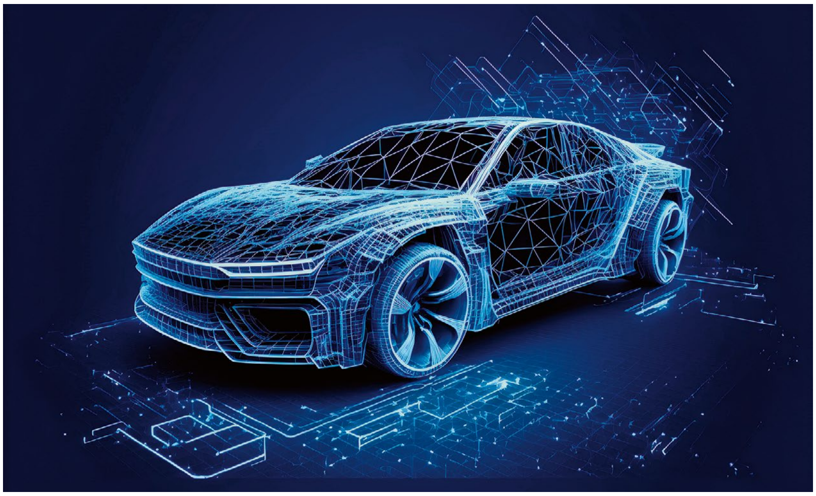
MIPI Alliance | **Update for Interface Specification**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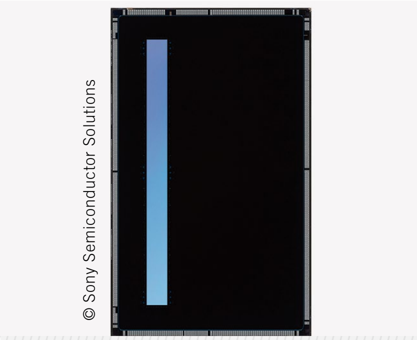
MIPI Alliance has released an update to its EMI-resilient C-PHY interface specification for cameras and displays. MIPI C-PHY v3.0 offers an 18-wire mode encoding option that increases the maximum performance of a C-PHY lane by approximately 30 to 35 %. This enables data rates of up to 75 Gbit/s over short cable connections, supporting the growing requirements of image sensors with ultra-high image resolution and quality in numerous application areas. The more efficient 32b9s encoding option transmits 32 bits over nine symbols and complements the advantages of MIPI C-PHY in terms of low electromagnetic interference and low power consumption. This supports applications with high-resolution image sensors, such as driver assistance systems that can analyze the movement and behavior of fast-moving objects under the most difficult lighting conditions.

© TDK

TDK | **Multi-layer Chip Inductors Series Expanded**

TDK has expanded its MPZ1608-PH series of multi-layer chip inductors. These products in the 1608 package size are designed for high currents in power supply units in automotive applications, among others. These large components achieve a rated current of 8 A. With dimensions of 1.6 × 0.8 × 0.6 mm, they halve the space required on the circuit board compared to circuits with two conventional 1608 chip resistors. In addition, with a specified operating temperature of up to +125 °C, they are designed for use in high-temperature environments.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Sony Semiconductor Solutions | **Stacked SPAD Depth Sensor**

Sony Semiconductor Solutions has announced the introduction of a stacked direct Time-of-Flight (dToF) SPAD depth sensor for LiDAR systems for distance measurement in vehicles. The IMX479 features high resolution and speed, operates using a line scan method, and uses a dToF pixel unit with 3 × 3 (horizontal × vertical) SPAD pixels as the minimum element to optimize measurement accuracy. In addition, the device structure supports a frame rate of up to 20 BpSi, which is the fastest frame rate to date for a SPAD depth sensor with 520 dToF pixels and a pixel size of 10 μm square.

MRS
Electronic GmbH & Co. KG
1.154.302.30
CAN I/O CC16WP
2MB CAN-CAN
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MRS Electronic | **New Version of CAN open Controller**

MRS Electronic has introduced a new CANopen version of the CAN I/O CC16WP. This compact controller is universally suitable for use in vehicles and mobile machines. It expands the MRS portfolio of CANopen slave modules, functions as a CANopen slave, and can be easily addressed via a higher-level controller (CANopen master) – for example, via Codesys. The CANopen stack used is based on the CiA 401 device profile, enabling standardized and seamless integration into existing networks. In addition to a high degree of configuration flexibility, users benefit from significantly simplified fault diagnosis.

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dSpace | **Real-time Platform Expanded**

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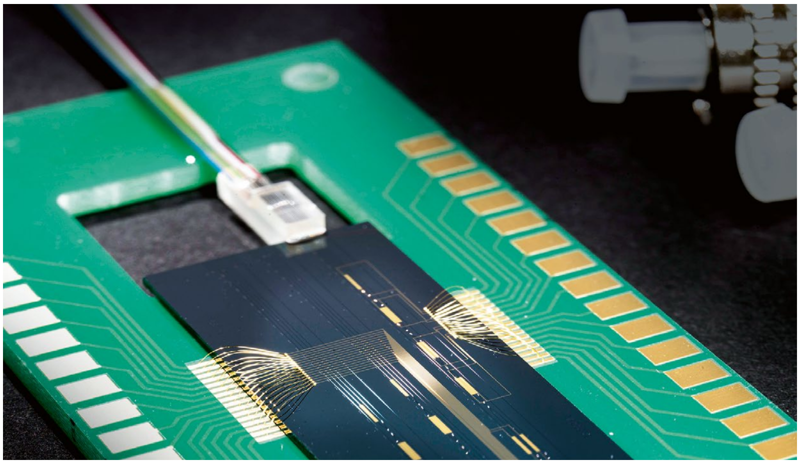
dSpace is expanding its Scalexio real-time platform for Hardware-in-the-Loop (HiL) applications with the new Scalexio FSX product line. This completes the product family and enables improved electrical fault injection, signal conditioning, and customer-specific extensions. The modular architecture of the system allows for the easy creation of scalable test solutions and shortens project-specific adaptations of the HiL system in the field, so that the test system can grow with the project over its lifetime. Scalexio FSX applications are designed, among other things, for the validation of real-time applications in the automotive industry. Particular emphasis was placed on seamless transition between systems. This means that not only real-time applications but also system configurations can be expanded and reused. In addition, the systems are easy to use, and hardware modifications and extensions can be carried out by users themselves.

Fraunhofer IOF | **Photonic Integrated Circuits**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Researchers at the Fraunhofer Institute for Applied Optics and Precision Engineering IOF have further developed Lithium Niobate-On-Insulator (LNOI) to build integrated optical circuits. This is said to be a breakthrough for photonic integrated circuits, which enable energy-efficient, fast, and scalable photonic systems. Unlike electrical ICs, these have waveguides instead of electrical conductors, and light signals are processed in small interferometers instead of transistors or gates. Both waveguides and interferometers can be manufactured in this way. The LNOI technology developed in the PhoQuant project at Fraunhofer IOF has the advantage of enabling processing speeds in the 100 GHz range, and the control voltage for the modulators is in the range of a few volts.

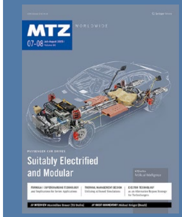
SIDE-VIEW MIRROR

ATZ worldwide 07-08/2025

Noise Optimization of Electric Drives Using the Blocked Forces Method

Easy and Reliable Modal Analysis with AI-assisted Tools

Interview with Dr. Dieter Höfler, Founder and CEO of Tectos

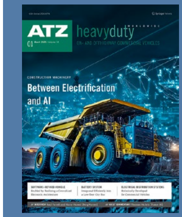


MTZ worldwide 07-08/2025

The Renaissance of Range Extenders

Development of Modular Application Software for Integrated Powertrain Control Systems

Interview with Prof. Maximilian Brauer, Head of the Vehicle Powertrain department at the Technical University of Berlin



ATZheavyduty worldwide 01/2025

Starting Module DynamicPerform for the Traxon Commercial Vehicle Transmission by ZF

Machine Learning Pipeline Supports AI-based Applications

Interview with Chief Technology Officer Harry Husted and Chief Strategy Officer Dr. Paul Farrell from BorgWarner

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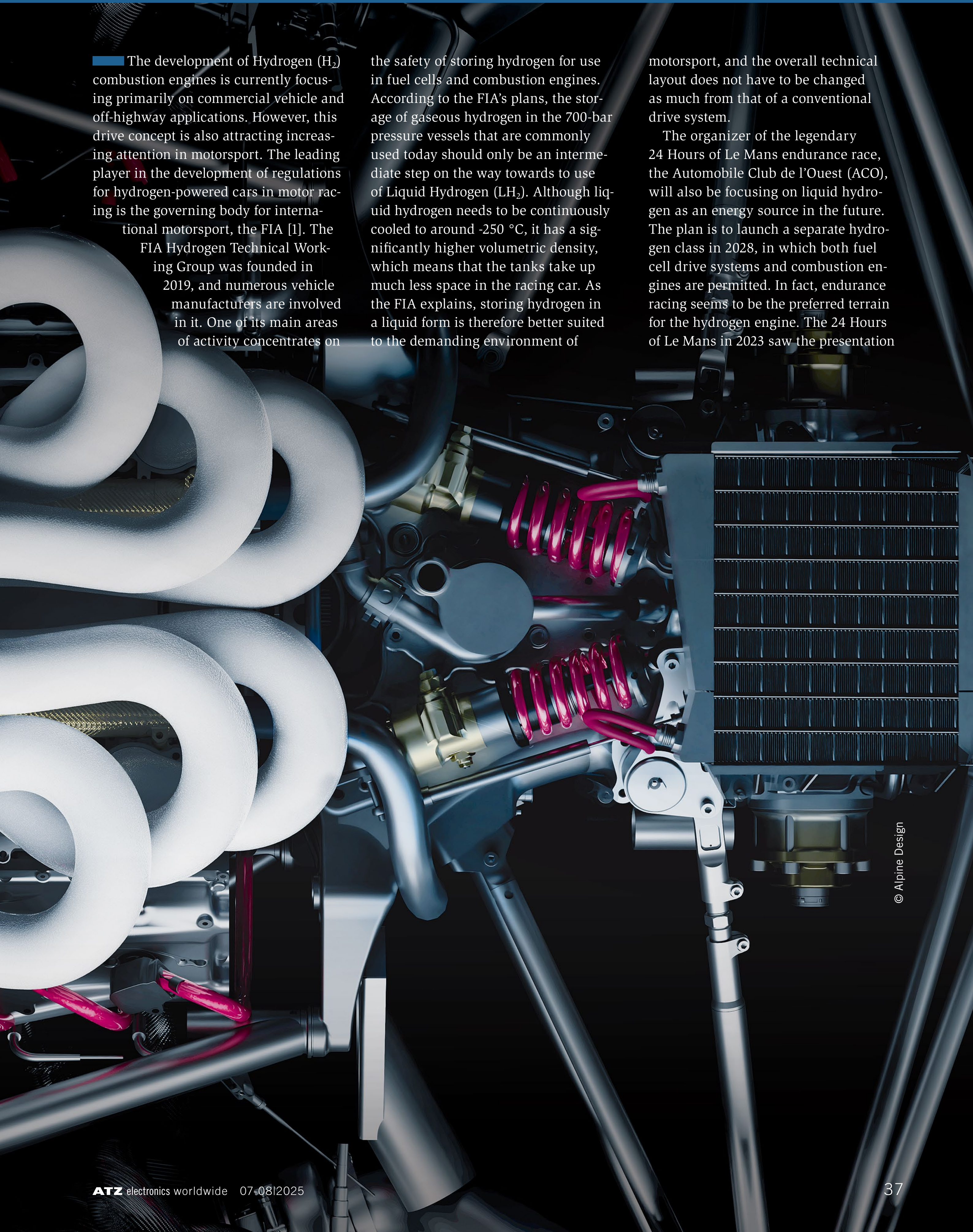
Hydrogen Gets Its Opportunity in Motor Racing

Compact, powerful, and allowing for fast refueling – in motor racing in particular, the hydrogen combustion engine offers advantages compared to an electric drive system. The organizers of major motor racing series are currently working on regulations for the use of hydrogen engines, while car manufacturers and suppliers are developing their technology. The first hydrogen-powered cars on the international motor racing scene will line up on the starting grid at the 24 Hours of Le Mans in 2028 at the latest.

The development of Hydrogen (H_2) combustion engines is currently focusing primarily on commercial vehicle and off-highway applications. However, this drive concept is also attracting increasing attention in motorsport. The leading player in the development of regulations for hydrogen-powered cars in motor racing is the governing body for international motorsport, the FIA [1]. The FIA Hydrogen Technical Working Group was founded in 2019, and numerous vehicle manufacturers are involved in it. One of its main areas of activity concentrates on the safety of storing hydrogen for use in fuel cells and combustion engines. According to the FIA's plans, the storage of gaseous hydrogen in the 700-bar pressure vessels that are commonly used today should only be an intermediate step on the way towards to use of Liquid Hydrogen (LH_2). Although liquid hydrogen needs to be continuously cooled to around -250 °C, it has a significantly higher volumetric density, which means that the tanks take up much less space in the racing car. As the FIA explains, storing hydrogen in a liquid form is therefore better suited to the demanding environment of motorsport, and the overall technical layout does not have to be changed as much from that of a conventional drive system.

The organizer of the legendary 24 Hours of Le Mans endurance race, the Automobile Club de l'Ouest (ACO), will also be focusing on liquid hydrogen as an energy source in the future. The plan is to launch a separate hydrogen class in 2028, in which both fuel cell drive systems and combustion engines are permitted. In fact, endurance racing seems to be the preferred terrain for the hydrogen engine. The 24 Hours of Le Mans in 2023 saw the presentation



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AVL H_2 ICE RACE
AVL RACETECH

© AVL

Four-cylinder hydrogen engine from AVL Racetech

of hydrogen project studies, as Bosch Engineering and Ligier Automotive launched their JS2 RH2 and Toyota unveiled its GR H2 Racing Concept.

TOYOTA GAINING EXPERIENCE ON THE RACETRACK

The Japanese car manufacturer was able to benefit from its experience in other racing series. Toyota has already been using a touring car with a hydrogen internal combustion engine in the Japanese Super Taikyu endurance racing series since 2021 [2]. The liquid hydrogen-fueled Corolla Sport has a converted gasoline engine taken from the Yaris GR. “Our concept for this project was to create a hydrogen engine by using as much of the existing internal combustion technology as possible. We thought that achieving this would enable the conversion of existing car engines to hydrogen, providing a powerful weapon in the quest for carbon neutrality,” said project leader Naoaki Ito. A key role in the success of the project was played by the supplier Denso, who developed the injectors for the direct injection of hydrogen into the turbocharged three-cylinder power unit. In the meantime, the hydrogen tank system of the Corolla Sport has even been converted from gaseous to liquid hydrogen [3].

Toyota is also part of a Japanese consortium that was founded in 2021 together with the companies Kawasaki, Subaru, Mazda, and Yamaha to carry out research into combustion engines powered by alternative fuels such as hydrogen. In the context of this cooperation, it was announced that Yamaha had developed a V8 hydrogen engine for Toyota. The unit is based on the 5.0-l engine in the Lexus RC F sport coupe, with modifications made to the injectors, cylinder heads, intake manifold, and other components. The engine delivers a power output of up to 330 kW at 6800 rpm and a maximum torque of 540 Nm at 3600 rpm [4]. We can assume that at least some of this engine technology will be used in the above-mentioned Le Mans sports car study from Toyota. In that car, the manufacturer is using a hybrid drive system with a hydrogen engine, but it does not provide any technical details [5].

DEMONSTRATOR VEHICLE FROM BOSCH ENGINEERING AND LIGIER

Bosch Engineering and Ligier Automotive, in contrast, are more forthcoming. The demonstrator vehicle with a hydrogen engine that was presented in 2023 is based on the Ligier JS2 R racing car, which has been fitted with a carbon-fiber monocoque chassis structure for weight and safety reasons. During the system development of the Ligier JS2 RH2, particular attention was paid to the design of the entire tank system and the safety concept. Continuous verification of safety during the development process was aimed at ensuring that the vehicle sets standards with regard to the functional safety of hydrogen-powered vehicles, while at the same time offering maximum system availability. In the current vehicle concept, the hydrogen is stored in 700-bar pressurized tanks. However, Bosch Engineering and Ligier Automotive have already carried out initial studies on the integration of liquid hydrogen systems into vehicles, and this could be used in future projects.

The power unit of the Ligier JS2 RH2 is a 3.0-l six-cylinder biturbo gasoline engine that has been converted to use hydrogen. In order to gain experience with a market-friendly, economically viable transition from gasoline to hydrogen, Bosch Engineering wanted to make as few changes to the components as possible when adapting the engine hardware to the new fuel. Various components were carried over unchanged from the series-production unit, including the crankshaft, valve train, cylinder head, pistons, and turbocharger assembly. Modifications were made to the injectors for the direct and port fuel injection as well as to the ignition system, while a water injection system was also integrated. “The development of hydrogen drive systems for motorsport enables us to bring particularly demanding technologies to the racetrack at an early stage, which can also have road reference. This gives us an innovative edge in future hydrogen projects, both in motorsport and for sports cars,” said Dr. Johannes-Jörg Rüger, President Bosch Engineering.

The fundamental challenges that arise in the use of H_2 in a high-performance combustion engine include higher component temperatures and the fast ignition characteristics, which, especially in the case of stoichiometric combustion, result in a pronounced pre-ignition tendency. This can be counteracted by such measures as lean-burn operation and/or water injection. “We use both possibilities. Lean-burn operation is used up to high load ranges, while additional water injection ensures internal cooling of the engine. This significantly reduces the tendency to pre-ignite, which increases the hydrogen injection window and thus the fuel quantity,” explained Lionel Martin, Senior-Product Manager H_2 Engines and Storage for Sports Cars and Racing Cars at Bosch Engineering. This engine concept ensures both lean-burn, low-NO_x combustion up to partial load and a very high specific power output. According to Bosch Engineering, systematic application enabled a power output of 443 kW and a torque of 680 Nm to be achieved, coupled with a very good transient response from the engine. The technology of the vehicle and its drive system has been described in detail in ATZ and MTZ [6, 7].

SUCCESSFUL TESTBED TESTING AT AVL

AVL Racetech, the motorsport department of AVL, has developed a hydrogen-powered 2.0-l racing engine in cooperation with the Hungarian research institute HUMDA Lab [8]. The four-cylinder basic engine is supplied by Audi. During testbed testing, the turbocharged unit developed a power output of 302 kW at 6500 rpm and a maximum torque of 500 Nm at 3000 to 4000 rpm. The air-fuel ratio (lambda) is 1 (stoichiometric combustion). The amount of air required, which is lower than with lean combustion, is provided by using a wastegate turbocharger designed specifically for that purpose. This concept also features water injection to avoid unwanted premature ignition. The AVL combustion

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Prof. Dr.-Ing. Hermann Rottengruber
Head of the Chair of Energy Conversion Systems for Mobile Applications of the Otto von Guericke University Magdeburg

2 QUESTIONS FOR ...

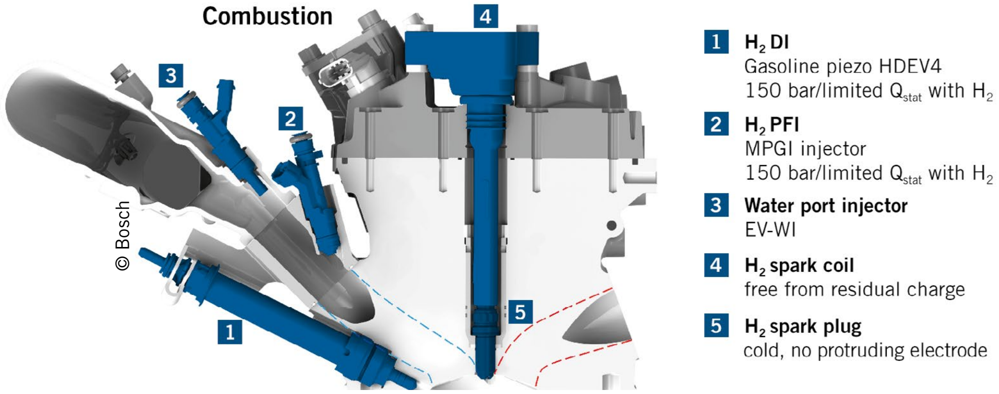
What potential and what challenges do you see when it comes to implementing hydrogen engine concepts in motorsport?

ROTTENGRUBER _ In my view, the key advantage lies is the possibility to refuel extremely quickly. This gives the hydrogen engine a clear competitive advantage, especially in long-distance races where pit stop times have to be minimized. However, the implementation of powerful, high-performance hydrogen combustion engines involves a number of technical challenges. The focus is on providing the required pressure level for high-pressure direct injection, which is essential for achieving a high power output. In addition, a complex supercharging system is necessary because of the transient operating behavior that is critical in motorsport, for example during rapid load changes.

In your opinion, what type of hydrogen storage system in the racing car would be better: storing liquid hydrogen or gaseous hydrogen at a pressure of 350 or 700 bar?

ROTTENGRUBER _ From a technical point of view, cryogenic (sub-cooled) or liquid storage of hydrogen is particularly suitable for use in motorsport. Firstly, it provides the highest volumetric storage density, which is a significant advantage when we want to maximize energy capacity with limited installation space and minimal weight. Secondly, so-called boil-off effects, in other words the uncontrolled evaporation of the cryogenic hydrogen, can be effectively reduced due to the predictable and constantly high fuel consumption during a race. A further technical advantage is the possibility of using the thermal energy stored in the cryogenic process in a targeted manner, for example to pre-compress the hydrogen before it is injected into the combustion chamber.

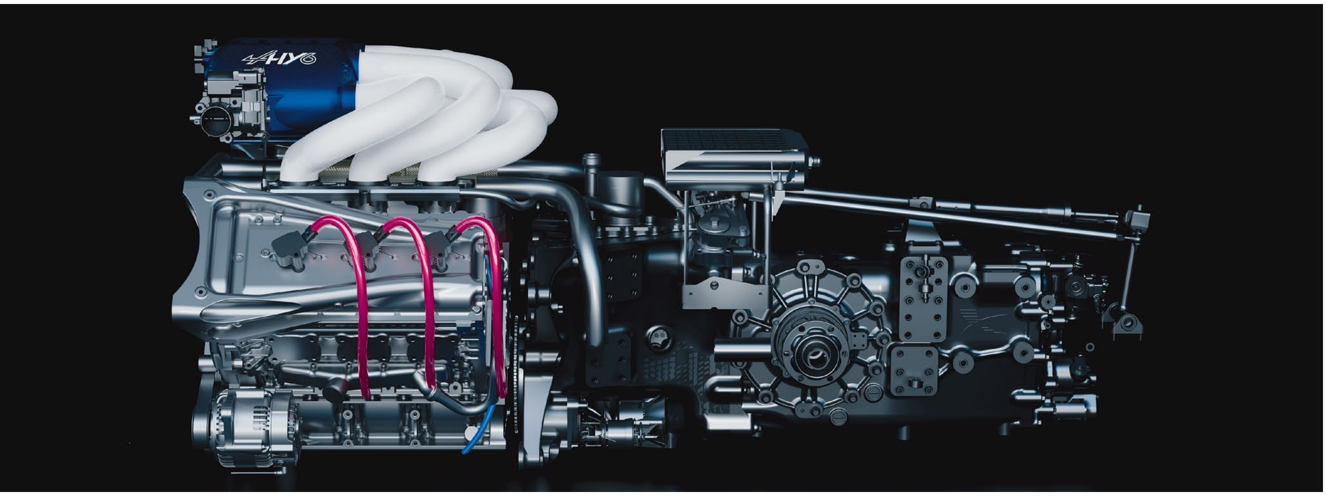
Cylinder head design of the hydrogen engine from Bosch Engineering and Ligier



process can also be operated without water injection with lean combustion. This variant is particularly suitable for engines with more cylinders and larger displacements. AVL had carried out detailed simulations in advance, and these displayed a very good correlation with the results achieved on the testbed. “At the end of 2022, we announced for the first time that we would be working on a 2.0-l hydrogen-powered racing engine with stoichiometric combustion and PFI water injection. Our goals were 500 Nm of torque and an output of up to 300 kW. We are proud to have been able to fully validate these figures on the testbed last year,” said Paul Kapus, Manager Development Spark Ignited Engines at AVL Racetech. The next milestone in the further development process is testing the new engine concept in a car on the racetrack. Ellen Lohr, Director Motorsport at AVL, added: “The results achieved by our hydrogen racing engine confirm that we are able to deliver an extremely competitive package with this technology. The goal of AVL Racetech is to lead motorsport into a sustainable future. With the development of the first racing engine developed under our own name as a high-performance H_2 internal combustion engine, we have taken another step closer to achieving this vision.”

ROLLING PROTOTYPE FROM ALPINE WITH FOUR AND SIX CYLINDERS

Alpine is another French sports car and racing car manufacturer that is working on hydrogen engines for long-distance racing cars [9, 10]. The Alpine Alpenglow Hy4 was unveiled in May 2024 at the Total Energies 6 Hours of Spa-Francorchamps FIA-WEC endurance race. As the company points out, the Alpine Alpenglow Hy4 is not a concept car, but has become a genuine rolling lab designed as a racing car with a carbon monocoque and a turbocharged 2.0-l four-cylinder engine that develops 250 kW. This features hydrogen direct injection at a pressure of 40 bar and water injection to reduce NO_x emissions. The Alpenglow Hy4’s three 700-bar pressurized tanks are located in the side pods and aft of the cockpit and are sealed off from the interior. The recently presented Alpenglow Hy6 is a further development of the Hy4 version and now has a V6 engine. According to Alpine, the 3.5-l biturbo power unit, which develops 544 kW at 7600 rpm and a maximum torque of 770 Nm at 5000 rpm, is a completely new design. “With the development of the Hy6 V6 engine, we are demonstrating our commitment to hydrogen research for motorsport applications with high performance levels. The Alpenglow Hy6 concept is the perfect



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Engine/transmission unit for the Alpenglow Hy6 from Alpine example of what is possible to achieve the essential step of reducing carbon emissions in motorsport," explained Bruno Famin, Vice President Alpine Motorsports. The special features of the super-square engine with a 95-mm bore and 82.3-mm stroke, which is designed for high revs of up to 9000 rpm, include a 100° cylinder-bank angle and dry sump lubrication. The development of the combustion chamber for homogeneous hydrogen combustion with indirect water injection was carried out at the company's own development center in Viry-Châtillon (France). Oreca was named as the external development partner. The engine concept of the Alpenglow Hy6 will initially be launched as a racing version, but it could be transposed to series production at a later date.

Richard Backhaus

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OPINION

"Monoculture is not a winning formula. That is true for both road vehicles and racing cars. In the transportation sector, focusing solely on electric mobility is leading to a dead end, as its widespread introduction is taking too long and electric drive systems cannot cover all requirements satisfactorily because of technical and economic shortcomings. In motorsport, we have reached the limits of what is possible using battery-electric powertrains, due to the need to meet the highest performance requirements at all times or due to the limited battery capacities during long-distance races. In both areas, on the road and on the racetrack, we need solutions that satisfy the demands. Here, the hydrogen combustion engine can sometimes be the better alternative."

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is Correspondent ATZ I MTZ I ATZelectronics.

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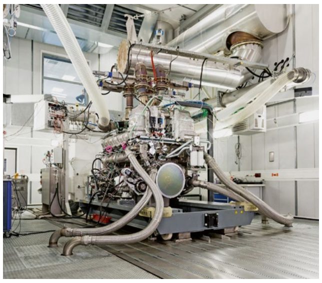
Manufacturers of large engines and their components must also pay more attention to the legal requirements for reducing emissions, although there will be no technology dictate here, as the number of applications and areas of use is simply too large. While construction machinery in urban areas, for example, can certainly be electrified, there will be no electric alternatives for shipping in the foreseeable future. Long periods of operation, TCO and difficult operating conditions require a variety of solutions. This makes it all the more important to verify the applications individually and to upgrade them for sustainability, be it through new technologies or by switching to appropriate energy sources. The Heavy-Duty Engines Conference is discussing increasingly solutions for the various application scenarios.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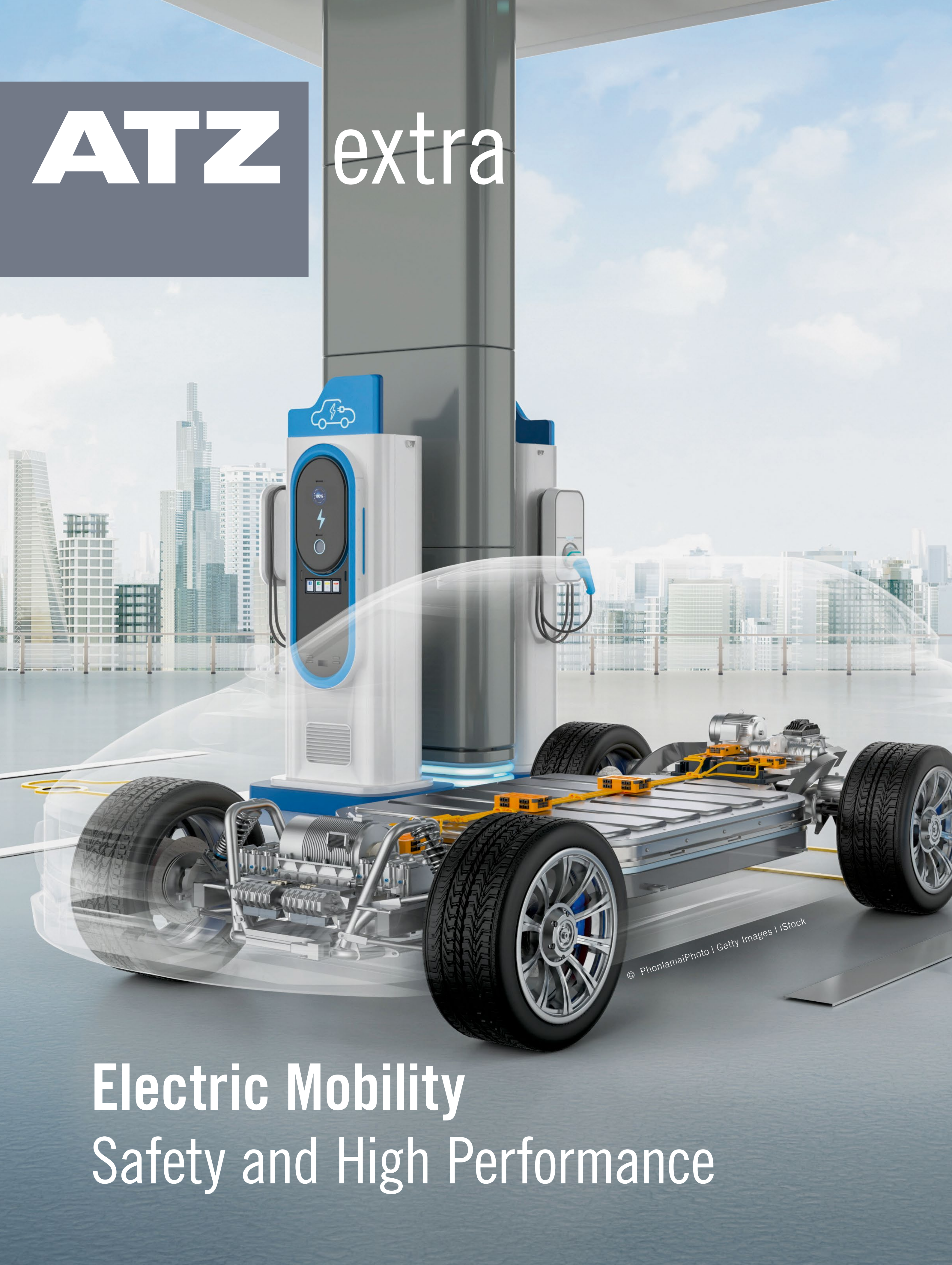

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Electric Mobility

Safety and High Performance

ELECTRIC MOBILITY

Safety and High Performance

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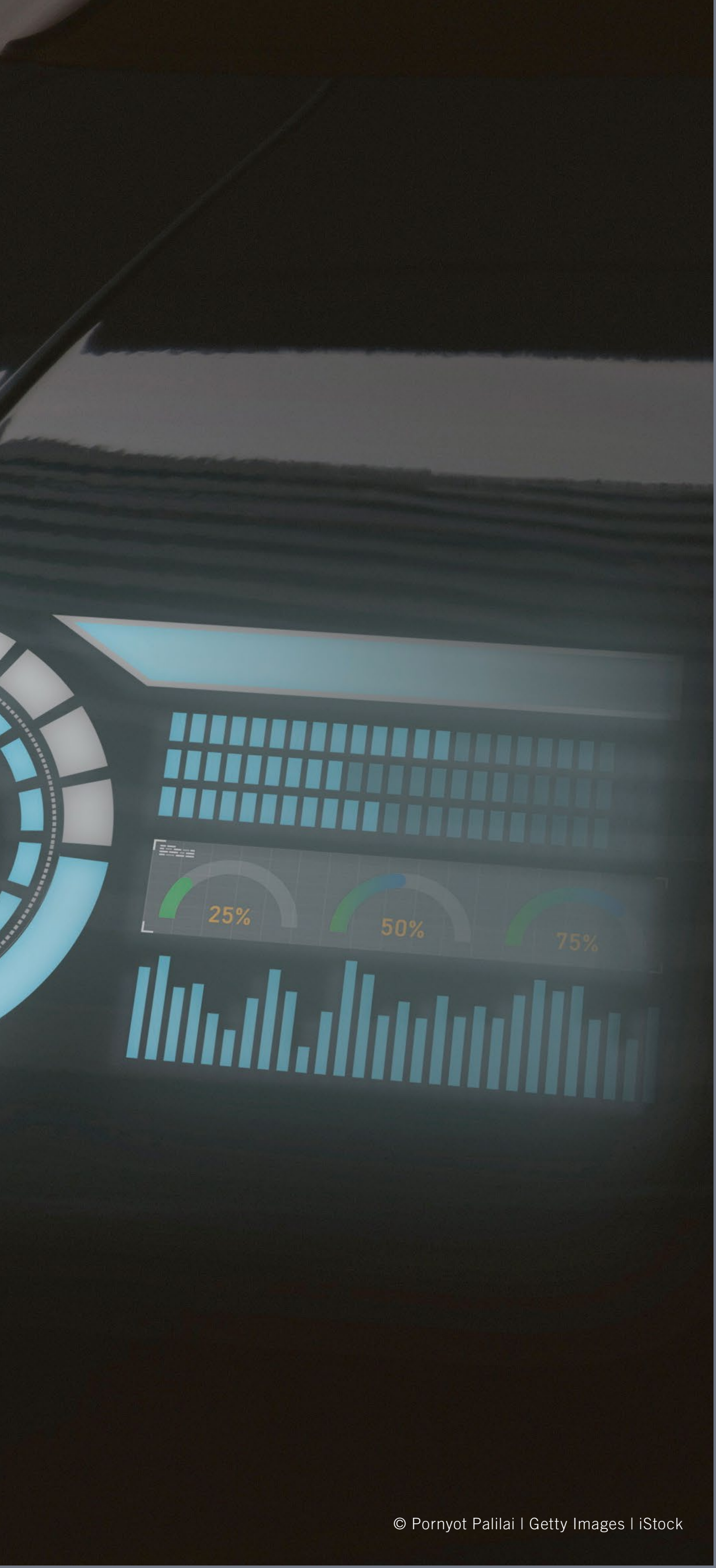

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The range of electric cars has tripled in the last ten years: according to the ADAC Ecotest, the average range in 2014 was 151 km and had risen to 425 km in 2024. The transport industry is also increasingly opting for electric drive systems. Even heavy commercial vehicles are now being powered by electricity, with ranges of up to 600 km. Two components have a great influence: the battery and the electric motor.

Compression pads between the cells, which help to build up external pressure, can extend the battery longevity. Since poor compression resistance can accelerate performance degradation, the pad material plays an important role. New cell-to-layer concepts, on the other hand, promise higher volumetric energy density. They also enable measures to be implemented to prevent thermal runaway – a factor that should not be underestimated in view of ever stricter safety requirements. Compliance with standards is also relevant for software systems that affect safety. Agile development methods can provide support. Suppliers of electric drives are faced with the challenge of ensuring both standardization and customization. A platform concept for 800-V architectures shows how both aspects can be considered.

Caroline Behle

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Electric mobility

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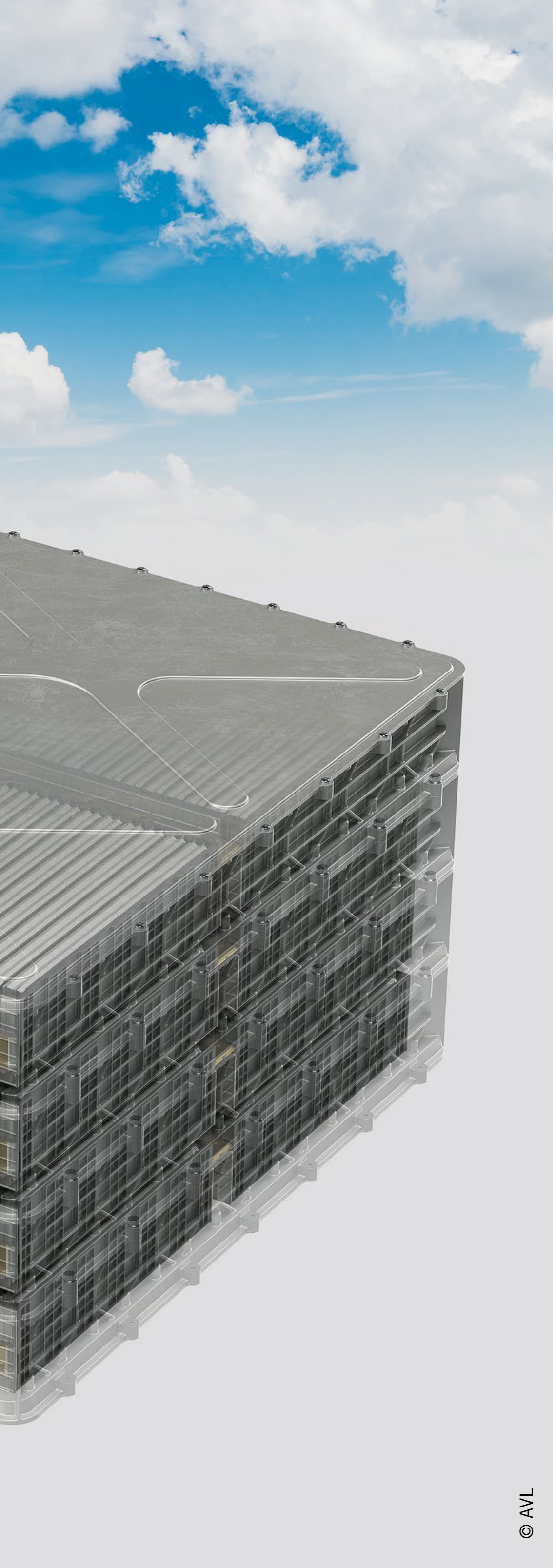
Cell-to-Layer Batteries for Commercial Vehicle Applications

In future battery systems for commercial vehicle applications, the key drivers are increasing range, reducing costs, enhancing reliability, and meeting strict safety standards. To achieve these goals competitively, the right approaches must be identified during the basic conceptual design of the battery structure, as demonstrated by AVL in this article.



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The electrification of the powertrain has now extended to the heavy commercial vehicle sector. A few years ago, fully electrified commercial vehicles were primarily used for light-duty inner-city distribution and delivery services. However, established manufacturers have recently added numerous battery-electric vehicles to their portfolios. Suitable for applications ranging from regional distribution to long-distance transportation, they represent a steadily growing alternative to vehicles with conventional drive systems. It is expected that the range in this segment will continue to expand.

With increasing electrification, the importance of electrified drivetrain components also rises, particularly the High-voltage (HV) battery due to its significant proportion of total costs. Besides product costs, the battery influences crucial vehicle characteristics such as range, service life, weight, and payload, making it a key component in commercial vehicles. Consequently, the development and integration of HV batteries are of great importance to vehicle manufacturers.

A key requirement for commercial vehicles is their long service life, which includes both the expected number of charging and discharging cycles and the overall service life (approximately 1.5 million km, which is some six times longer than that of a passenger car). This requires robust solutions in product development. Mechanical integration and thermal management are vital to ensure that battery cells are conditioned and age evenly. Cost and robustness requirements significantly influence the development of commercial vehicle batteries, especially in cell selection. It is essential to find a balance between properties such as parts costs, availability, energy content, and service life which leads to decisions regarding cell chemistry and cell type (cylindrical, prismatic, or pouch).

Safety is a high priority in development, especially for batteries with large energy content. Preventing cell outgassing from causing thermal runaway in neighboring cells is crucial. This prevention of thermal propagation is not only relevant to safety but is sometimes a prerequisite for homologation, requiring intensive development and validation loops. The late availability of test results in the overall system further complicates the process.

The sum of various requirements makes development a complex challenge, as general requirements such as weight and component quality must also be considered. Despite these challenges, development goals and boundary conditions often lead to similar solution approaches. Therefore, there are many similarities between the batteries for battery-electric commercial vehicles currently on the market, summarized here as the state of the art.

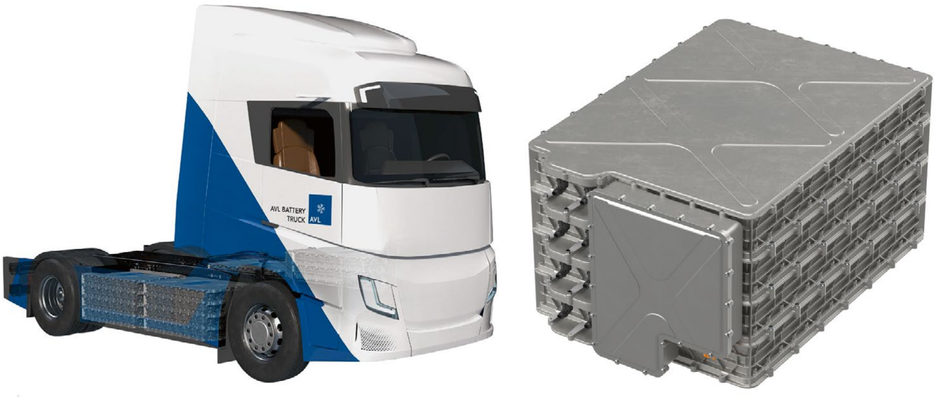

FIGURE 1 Battery structure according to the current market situation (© AVL)

CURRENT BATTERY SOLUTIONS AND NOVEL CELL-TO-LAYER APPROACH

A typical state-of-the-art battery is shown in **FIGURE 1**. It consists of a distributed battery system with several sub-batteries attached to the lead frame. These sub-batteries are composed of layers stacked on top of each other, allowing for an equal-parts approach and economies of scale through multiple installations. The housing parts of the layers are typically made of cast aluminum as the high production volume offers cost advantages compared to other manufacturing processes [1].

In addition to the housing structure, each layer also contains the cell modules, cooling systems, busbars, and module controllers. The cell modules are generally interchangeable subsystems, adhering to a modular design approach. The number of cells and dimensions of these modules are adapted to the housing structure to ensure optimal utilization of the installation space, thereby achieving high energy content. However, even higher energy densities can be attained with a new cell-to-layer approach, which largely eliminates structural module parts, allowing the battery housing to assume this function. This increase in packing density can be leveraged to extend the vehicle range or to favor the use of more cost-effective cell chemistries, as their lower energy density is at least partially compensated by the cell-to-layer approach. Using more cost-effective, lower-energy cell chemistry can offer advantages in certain domains. For instance, Lithium Ferrophosphate (LFP) cells are easier to protect against thermal propagation and exhibit lower aging and charge-dependent thickness changes. Compared to higher energy density cell chemistries, these properties facilitate easier cell integration.

Additionally, cell-to-layer approaches provide the opportunity to utilize cell formats that have not yet become established in commercial vehicle applications. For example, while prismatic cells are predominant in current commercial vehicles, pouch or round cells are rarely used. Nevertheless, these cell formats can offer advantages over prismatic cells in certain areas.

COMPARISON OF CELL-TO-LAYER CONCEPTS

The trend toward more affordable batteries with longer ranges prompted AVL to develop and compare innovative concepts using different cell formats. As a result, new solutions are presented, showcasing the potential for future commercial vehicle batteries. External interfaces, such as coolant connections, HV connectors, and screw connections, were kept consistent across all approaches. The layers can be stacked vertically, allowing flexible adaptation in height to the installation space conditions in the vehicle.

An equal voltage level of 350 V (nominal) for the layer was defined as a boundary condition for all concepts, resulting in an interconnection of 96s1p (96 cells connected in series, one row parallel) for the pouch and prismatic cells used, and an interconnection of 96s4p for the round cells. With this voltage, a system voltage of 700 V can be achieved with a 2s2p circuit of layers, enabling the use of common electronic components for conventional 800-V architectures.

The layer concept with pouch cells is illustrated in **FIGURE 2**. As a basic unit, two pouch cells are combined with an enclosing thermal barrier, which has a predetermined breaking point on the underside for a defined degassing opening. The cell pairs are lined up with intermediate cell material to form a cell stack which is clamped in a device and welded at the cell poles. A Flexible Printed Circuit (FPC) board with voltage taps and temperature sensors is mounted on the cell stack and plastic end plates are arranged on the sides of the cell stack. This pre-assembled braced stack is inserted into the die-cast housing from above and attached to a steel base plate on the underside with an adhesive connection. The cells are cooled using a cooling plate, which is attached to the top of the cell stack.

The cell-to-layer concept with prismatic cells is illustrated in **FIGURE 3** (left). For this concept, prismatic cells were

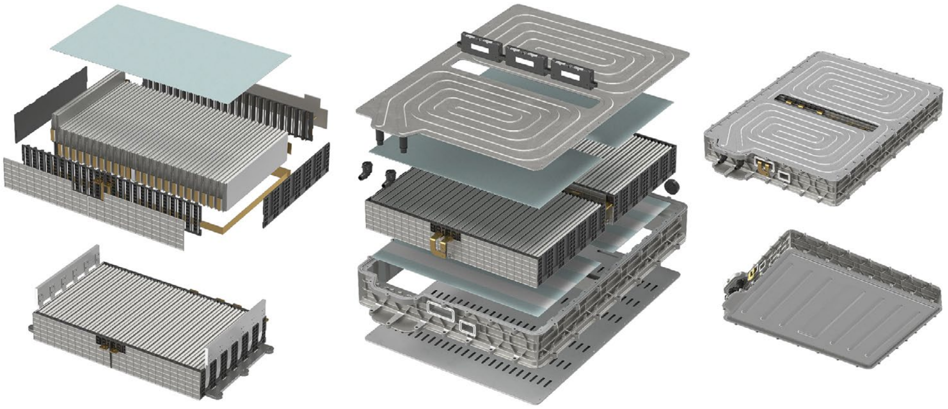

FIGURE 2 Assembly overview and housing integration with a pouch cell (© AVL)

chosen with poles on the top and a degassing opening on the bottom. The cells are pressed into a stack with intermediate cell material and plastic end plates. Cell connectors, voltage taps, and temperature sensors are arranged on the top side. The cell stacks are inserted into the housing in a clamped state and glued to the base plate. The cooling plate regulates the cell temperature directly via the busbars and laterally offset in height via the cell housing. To achieve this, the cooling plate must have an electrically insulating coating, and production-related height tolerances must be bridged using a heat-conducting pad.

The concept with round cells is shown in **FIGURE 3** (right). The cells are preassembled in a plastic carrier and glued to the base plate. This concept does not require the cells to be compressed. The electrical cell connection is made on the top of the layer, where the FPC with busbars, voltage, and temperature sensors is located. Cooling is again provided at the top of the cell stack, ensuring a good thermal connection to the cell connectors.

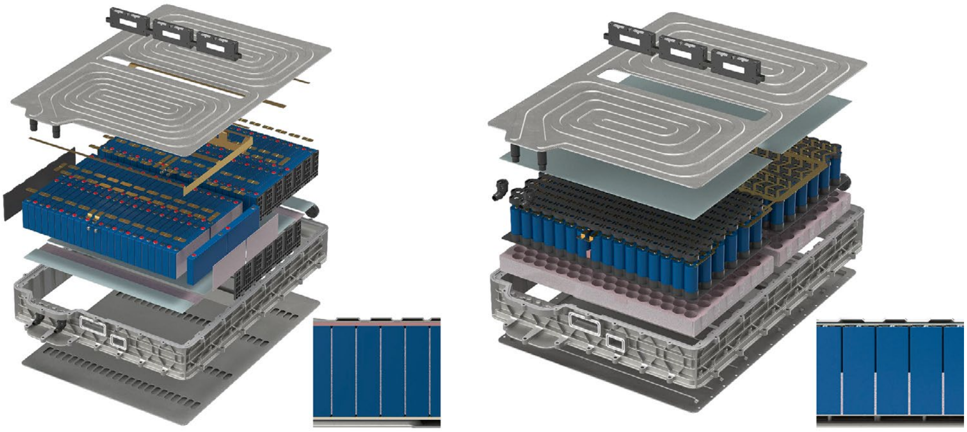

FIGURE 3 Layer structure with prismatic (left) and cylindrical cell (right) (© AVL)

SAFETY AND GAS ROUTING CONCEPT

An important aspect for all concepts is the controlled gas flow in a thermal runaway event of the battery cell. This assessment is based off of AVL's vast library of experience in terms of simulation and testing of an extensive variety of battery applications. In all three concepts shown, the gas is directed into a base plate via defined openings, **FIGURE 4**. The base plate consists of two welded steel plates, which form the supporting structure for the cells and separate the gas from the HV and Low-voltage (LV) components. This separation minimizes the risk of thermal propagation due to arcing, which is promoted by conductive particles in the gas [2]. The base plate features a chamber system where the gas pressure is released after exiting the cell and is then guided toward the degassing valves through a labyrinthine path. Particle size as well as gas velocity are being considered when designing the gas routing and temperature profiles. The precooled gas is channeled from the steel plate into the cast channel of the layer frame, where it is connected to the degassing valve.

EVALUATION OF THE CONCEPTS

An important comparative value for evaluating cell-to-layer approaches is the volumetric energy density. The concepts developed with prismatic and pouch cells show an improvement of approximately 8 to 9 % compared to the current state of the art. The cell-to-layer concept with round cells shows a slightly smaller improvement of 7 %. The comparison was based on energy densities at the cell level with 680 Wh/l for prismatic cells, 750 Wh/l for cylindrical cells, and 730 Wh/l for pouch cells. Despite the slightly lower energy density of the round cells, this cell format offers several advantages. The structurally rigid housing of the cylindrical cell does not require pre-compression, simplifying assembly, especially with the cell-to-layer approach. Additionally, the smaller cell releases less energy in the event of thermal runaway, making it easier to control. With small cells, higher system voltages well over 800 V can be easily achieved in series connection, whereas large-format prismatic cells do not offer this flexibility.

Even when considering the overall advantages and disadvantages of the concepts, no clear favorite can be identified, **FIGURE 5**. AVL's cell-to-layer-approach as it was described, demonstrates advantages for each cell type. The criteria must be evaluated and prioritized for each individual case and vehicle type. Product cost and vehicle attributes like weight, payload, and range have to be assessed from a complete vehicle perspective. The named safety concepts – AVL is working here on no-flame-out and no-gas-out technologies – are playing an important role especially with commercial vehicles being outfitted with high battery capacities. Cell-to-layer will

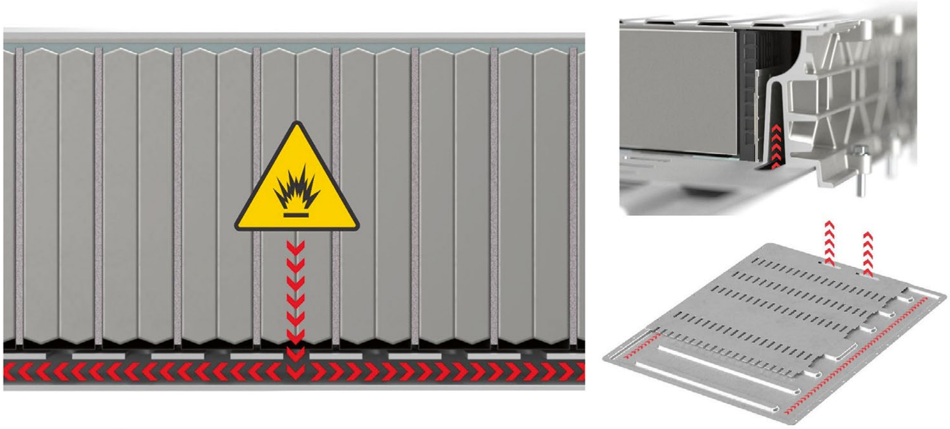

FIGURE 4 Controlled gas flow during thermal runaway of the cell (© AVL)

	Energy density (cell)	Packaging	Cooling	Venting	Cell design flexibility	Other considerations
Pouch	🟩	🟨	🟩	🟥	🟩	+ Flexible cell-to-cell connection - Compression force (+) Over 800 V easily feasible
Prismatic	🟨	🟩	🟩	🟨	🟨	+ Mechanical strength + Internal safety device (-) Compression force
Cylindrical (large)	🟩	🟨	🟩	🟩	🟥	+ Economic manufacturing + No compression force (+) Over 800 V easily feasible

FIGURE 5 Overview and evaluation of different battery formats (suitability: red = less suitable; yellow = neutral; green = suitable) (© AVL)

be the next technological step of battery development, no matter the cell type.

SERVICE AND RECYCLING

For servicing, the electronic components and the Battery Management System (BMS) can be replaced directly via the service cover of the Battery Disconnect Unit (BDU) housing. Disassembly down to the layer level is relatively simple by loosening the screw connections from the top and bottom covers, BDU housing, and the layers themselves. The coolant connections and degassing valves can be dismantled using a plug-in or twist connection. Accessibility to the cell control unit at the layer level is also ensured, thanks to a corresponding cutout in the cooling plate. This approach allows individual layers with reduced service life to be replaced during servicing and their continued use for stationary applications is also conceivable.

For recycling at the end of the battery's life, it is envisaged that the base plate with the glued-on cells can be removed from the frame as a single unit using a dismantling device after the cells have been discharged, **FIGURE 6**. The aluminum frame can be dismantled down to its original cast state, free of interfering steel attachments. Care must be taken in the design to avoid adhesive and sealing residues on the component as much as possible.

SUMMARY AND OUTLOOK

Cell-to-layer approaches offer several advantages over the current state of the art. By integrating the cells directly into the battery housing, volumetric energy density and vehicle range can be increased. Additionally, the elimination of structural module components reduces the overall number of components, potentially resulting in cost savings. The concepts presented by AVL demonstrate that, in addition to the prismatic cells currently in use, round and pouch cells are also suitable for cell-to-layer concepts. Measures can be implemented to address thermal propagation, ensuring compliance with future safety standards. AVL sees promising potential in these design concepts, which need to be further developed as part of a holistic vehicle approach. Attractive Total Cost of Ownership (TCO) is mandatory for market success of commercial vehicles. The demonstrated cell-to-layer apporach will play an important role there.

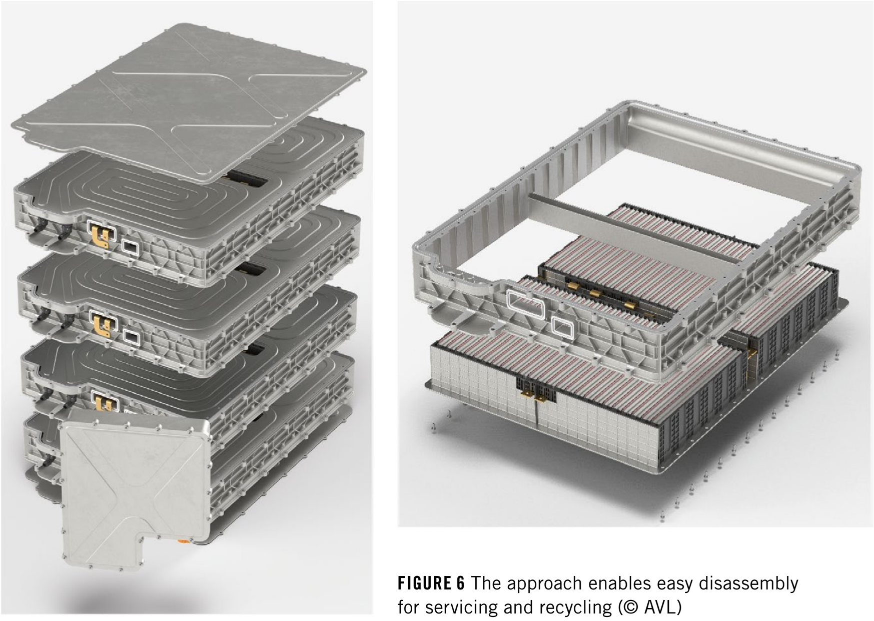

FIGURE 6 The approach enables easy disassembly for servicing and recycling (© AVL)

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BORGWARNER

Managing Future Standards for the Thermal Propagation of Lithium-ion Batteries

Thermal propagation is one of the most challenging areas of development for lithium-ion traction batteries for electric vehicles. The relevant legal safety requirements are currently being updated and tightened. Meeting these safety targets will be crucial for future battery developments. FEV shows which methods and test concepts are necessary to achieve this.

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Thermal Propagation (TP) describes the process of Thermal Runaway (TR) of a single cell – originally caused by a Cell Internal Short Circuit (CISC) – and the associated risk of thermal “infection” of neighboring cells that may also experience TR. It can cause the thermal event to spread throughout the entire battery system (Rechargeable Electrical Energy Storage System, REESS). This process can be accompanied by fire and/or explosions and will usually result in significant release of smoke and gases, **FIGURE 1**.

The potential hazards to people in the surrounding of the battery or vehicle resulting from these events must be minimized by safety regulations worldwide. However, the approaches on how to prevent a TP remain different for the various target markets. It needs to be mentioned that not every TR of a single cell necessarily leads to TP and related hazards [1]. Depending on the cell characteristics and on the battery system design, it is quite possible to limit the thermal event to a single cell or the TP to a module of the battery.

REQUIREMENTS FOR MINIMIZING THERMAL PROPAGATION

Regulations require the manufacturer to demonstrate through simulations and related validation results that the battery system meets the TP safety requirements of local regulations. However, authentically reproducing the failure mode of a CISC in a test environment is challenging. The most estab-

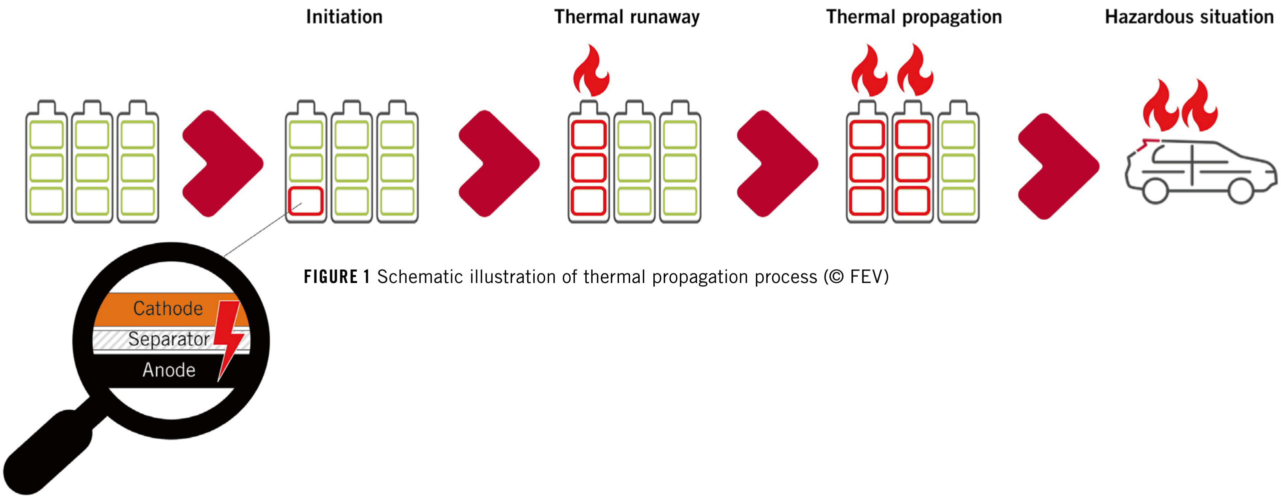


FIGURE 1 Schematic illustration of thermal propagation process (© FEV)

lished procedures to initiate a single cell TR caused by a cell internal short circuit (also referred to as “trigger methods”) are:

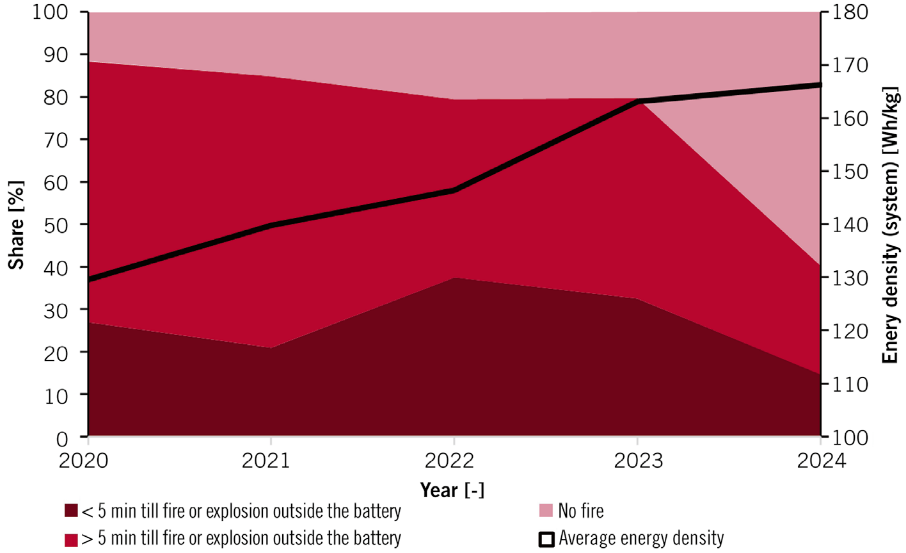
– external (rapid) heater: A heating element is used as external heat source applied to the outer surface of a target cell to locally melt down the separator of the target cell and thus create a CISC.
– internal heater: A heating element is installed within the target battery cell. The mechanism is basically the same as when using the external heater (local melting of separator).
– nail penetration: A nail, usually made of conductive material (steel), is inserted into the target cell, pierces the separator, and thus creats a CISC.

All the above-mentioned trigger methods have different advantages and disadvantages and pose different experimental challenges like accessibility of the target cell or re-sealing the cell- or pack housing. However, all of these methods are routinely executed in numerous tests at the FEV battery test center in (FEV eDLP) in Sandersdorf-Brehna (Germany).

The described safety risk of TR in current lithium-ion battery cells, potentially leading to TP and endangering people in the vicinity, was recognized already years ago. Therefore, enormous efforts have been made to define appropriate safety requirements that are incorporated into the homologation requirements to ensure the safety of vehicle occupants and bystanders. As these homologation requirements are currently under revision, the related technical requirements will be strengthened in the near future. UN R100 will incorporate new TP requirements in the upcoming revision 5, which will include specific TP test requirements for the first time and will not only address the battery standalone TP performance but also consider the overall system behavior of the battery being installed inside the vehicle. Systematic TP safety studies performed by FEV have demonstrated the significant different results of TP tests executed on REESS level compared to test setups with the battery installed within a vehicle body.

At the same time, the recently introduced FMVSS 305a/part 561 will define related safety requirements for the US market, but without specifying explicit test procedures to demonstrate safety compliance. However, the most stricter TP requirements are the updates of the Chinese GB 38031. This does not permit the occurrence of fire outside the battery at any time during the test, whereas in the current revision of the standard, this requirement is restricted to the first 5 min after the start of the TR. Due to the increased TP requirements, a targeted design toward TP-safe batteries will become even more important in the near future.

FIGURE 2 Historical trends of TP tests executed by FEV (© FEV)



COMPARISON OF CURRENT BATTERY SYSTEMS

In recent years, FEV has performed hundreds of TP tests. Statistical evaluation of results indicates interesting trends regarding the TP performance of current battery system architectures. For evaluation, the currently valid compliance criteria of GB 38031-2020 and AIS-038 Rev. 2 have been considered as benchmarks. This means that the REESS in a component-based test shall not show any external fire or explosion outside the battery pack within 5 min after triggering the TR. Results being clustered in the group of “no fire” represent those tests which do not show any fire at all. This result is often identical to “no TP” batteries, however this result also contains experiments which do show a (sometimes complete) propagation but no fire outside the pack.

Particularly important is that already today about 50 % of all TP tests performed at FEV eDLP comply with the demanding legislative TP requirements of the future GB 38031 standard and do not show any fire or explosion outside the battery, **FIGURE 2**.

The statistical share of “no fire” batteries has increased over the recent years from 10 % in 2020 to roughly 50 % in 2024. This result is even more promising, as the average energy density of TP tested batteries increased by 25 % during the same period.

A clustered presentation of TP performance in dependency on the gravimetrical energy density is shown in **FIGURE 3**. It can be seen that with increasing energy density, the statistical probability of failing the acceptance criteria increases. However, every fifth battery shows no external fire at all, even at high energy densities above 150 kWh/kg. About two-thirds of high energy density battery systems meet the 5 min criterion and almost 90 % of low energy density battery systems (<100 kWh/kg) meet this criterion. On the one hand, **FIGURE 3** shows an obvious trend: the higher the energy density, the higher the (statistical) probability of failing the test. On the other hand, the numbers shown may be interpreted in such a way that the increasing challenges arising from higher energy density can be overcome by installation of smart mitigation measures, as for example a reasonably chosen cell and thoughtful integration of the cell into the battery architecture. Such a “TP targeted development” of battery systems requires additional considerations of multiple influencing factors and derived design measures, which are sometimes conflicting with other development targets like high energy density. However, FEV has demonstrated in the past that battery designs, which are even extremely challenging regarding the TP safety properties, can be post-optimized to comply with TP safety requirements.

To support design decisions (both in bottom up and also post-optimization of existing battery designs) and to reduce testing efforts, FEV has developed a TR/TP simulation methodology. This methodology includes flexible numerical models, each capable of simulating different phenomena during TR/TP. A detailed thermal model has been developed in comsol Multiphysics or StarCCM+ and a Computational Fluid Dynamics (CFD) model of the vent gas flow has been created in StarCCM+. Within StarCCM+, both models can be fully coupled, **FIGURE 4**.

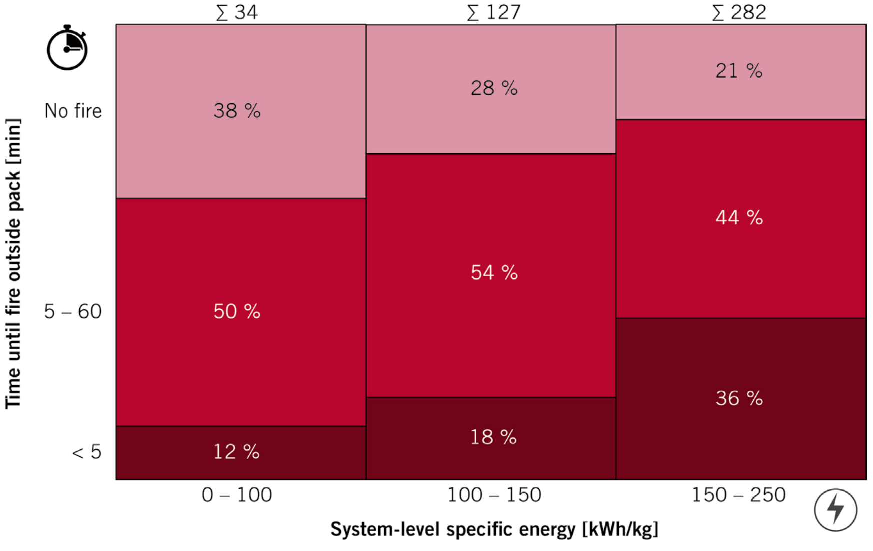
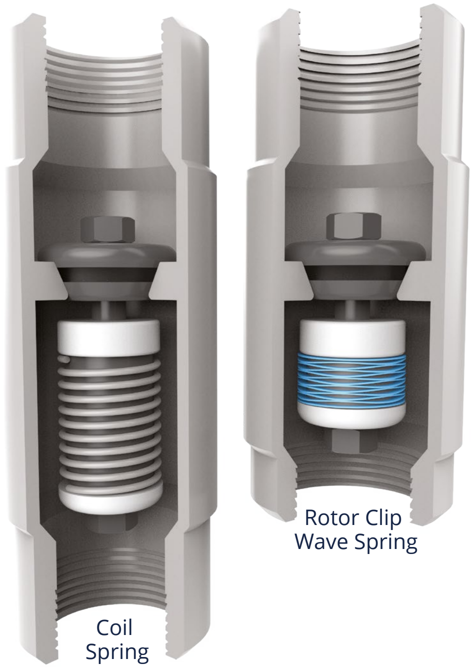


FIGURE 3 Relative distribution of TP performance in dependency on energy density on system level (© FEV)



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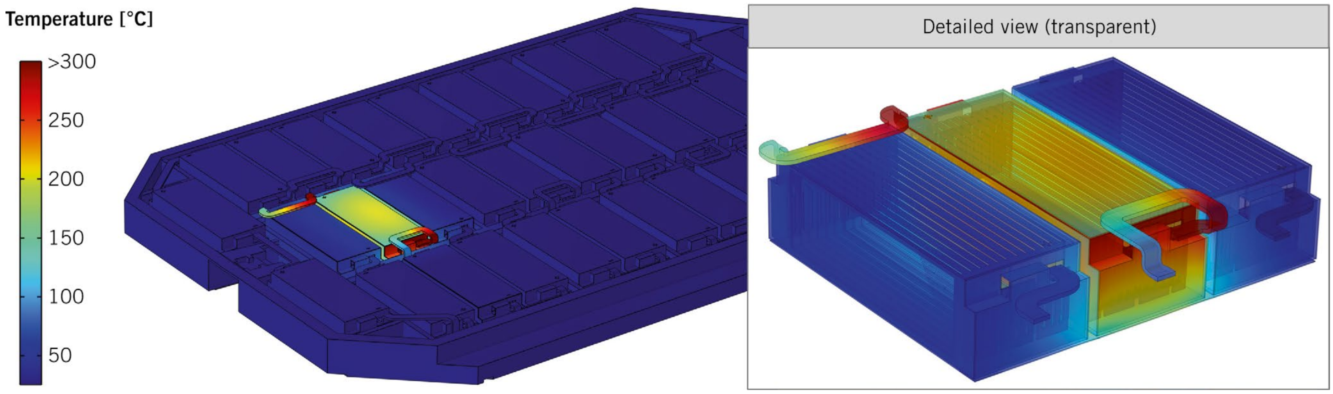

Temperature [°C]
>300
250
200
150
100
50
Detailed view (transparent)

FIGURE 4 Example of a thermal propagation simulation (© FEV)

COMBINED SIMULATION AND TEST STRATEGY

Testing is crucial in every phase of high-voltage battery development and is essential for concept validation and homologation. At FEV's eDLP, numerous tests can be conducted to support design and simulation efforts. For TR and TP mitigation, a cascaded testing approach is effectively used. This method provides the necessary measurement results for the initial parameterization, adaptation, and validation of various simulation models. By conducting extensive simulations simultaneously, effort and costs are minimized. **FIGURE 5** illustrates an example of the cascaded test procedure, ranging from single cell to full pack testing.

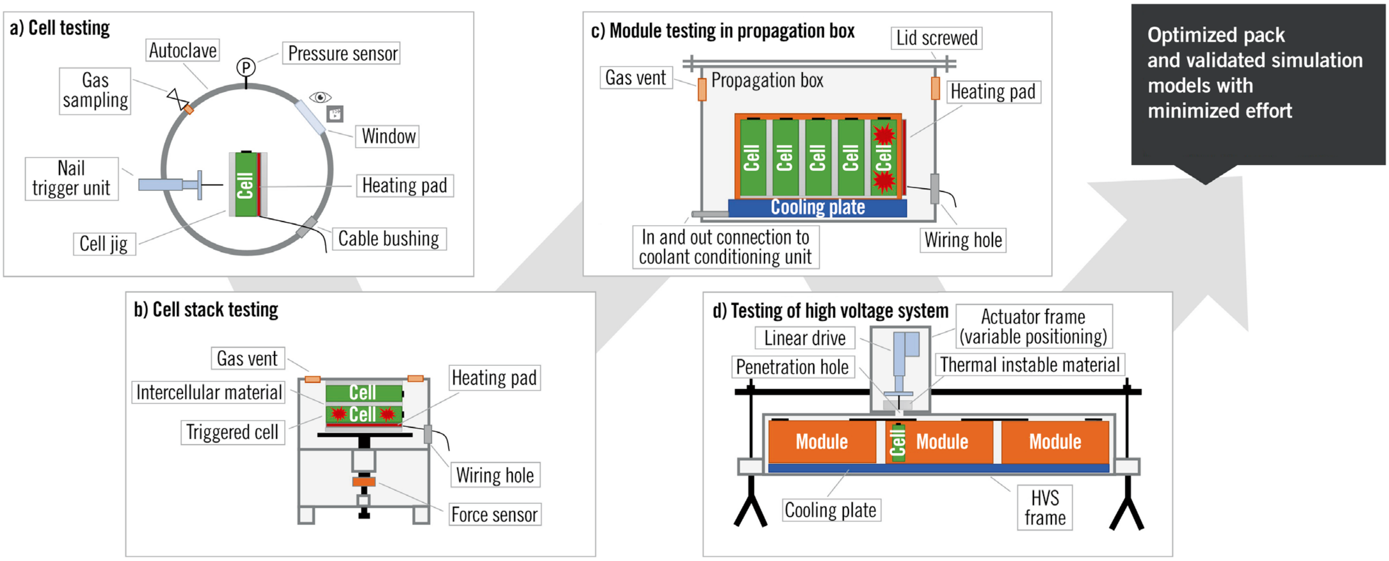
As mentioned before, TR behavior varies significantly from cell to cell, making single cell tests essential to identify specific TR characteristics. These tests are typically conducted in an (adiabatic) autoclave, **FIGURE 5** (a). This setup provides a confined environment for the Device Under Test (DUT) and allows for the measurement of relevant data such as vent gas amount and composition or the onset temperature of TR. Depending on the equipment manufacturer or test institute, the autoclave may have different features, such as varying trigger methods, in-situ or ex-situ gas analyses, or the capability for (thermal) video recording during the test. FEV has recently established a new, self-built autoclave where large cells can be thoroughly characterized.

Cell composite tests, **FIGURE 5** (b), offer a convenient way to investigate intercellular and thermal insulating materials for their propagation behavior, focusing on preventing thermal infection of neighboring cells. Additionally, geometric solutions can be used to explore fire suppression measures.

The propagation box, **FIGURE 5** (c), allows for the investigation of different cooling strategies or active extinguishing concepts for individual modules or module groups to prevent TP. One major advantage is the variable positioning of the trigger and ample space for the necessary additional measurement equipment.

Furthermore, FEV offers tests for entire High-voltage Systems (HVS) required for homologation, followed

FIGURE 5 Cascaded test approach from single cell to full pack testing (© FEV)


a) Cell testing
Autoclave
Pressure sensor
Gas sampling
P
Window
Nail trigger unit
Cell
Heating pad
Cell jig
Cable bushing
b) Cell stack testing
Gas vent
Intercellular material
Cell
Cell
Heating pad
Triggered cell
Wiring hole
Force sensor
c) Module testing in propagation box
Lid screwed
Gas vent
Propagation box
Heating pad
Cell
Cell
Cell
Cell
Cell
Cooling plate
In and out connection to coolant conditioning unit
Wiring hole
d) Testing of high voltage system
Linear drive
Actuator frame (variable positioning)
Penetration hole
Thermal instable material
Module
Cell
Module
Module
Cooling plate
HVS frame
Optimized pack and validated simulation models with minimized effort

by disassembly and detailed analysis, **FIGURE 5** (d). This enables direct evaluation of the effects of active separation of HV lines, the condition of insulating materials, and the occurrence of arcs.

SUMMARY AND OUTLOOK

The successful development of a battery system that meets future legal requirements regarding TP safety is challenging and an extremely multidisciplinary exercise. Not only the knowledge about (upcoming) regulatory requirements itself and their interpretation is of importance. In addition, a focused development toward the safety targets with highly integrated software development, simulation and validation activities on cell, subsystem and system level as well as the application of best practices for test execution and data evaluation is mandatory to ensure a safety-compliant battery system. FEV can support the development of such TP-safe battery systems along the whole development chain. For this, the company is making use of a detailed overview of the legislative landscape, together with strong expertise in development, simulation, and validation of battery systems based on the experiences gained in numerous battery projects for various applications. For battery design, the presented tool and methodology chain, which includes advanced simulation tools for validating design measures and a cascaded testing approach to initially parameterize the simulation models through cell tests and further refine them with increasing sample size, offers great advantages in battery development and increases vehicle safety for customers.

FEV's TP development and validation plan combines expertise in cell characteristics, design experience, simulation methodology, and software development into a focused yet cost-effective strategy to achieve tomorrow's thermal propagation safety goals today.

REFERENCE

[1] MacNeil, D. D. et al.: Rapid Heating Test Methodology: Vehicle (using cylindrical cells) Test. Online: https://wiki.unece.org/download/attachments/177242909/EVS25-E1TP-0400%20%5BCA%5DSingle%20Cell%20Thermal%20Runaway%20within%20EV.pdf?api=v2, access: April 29, 2025

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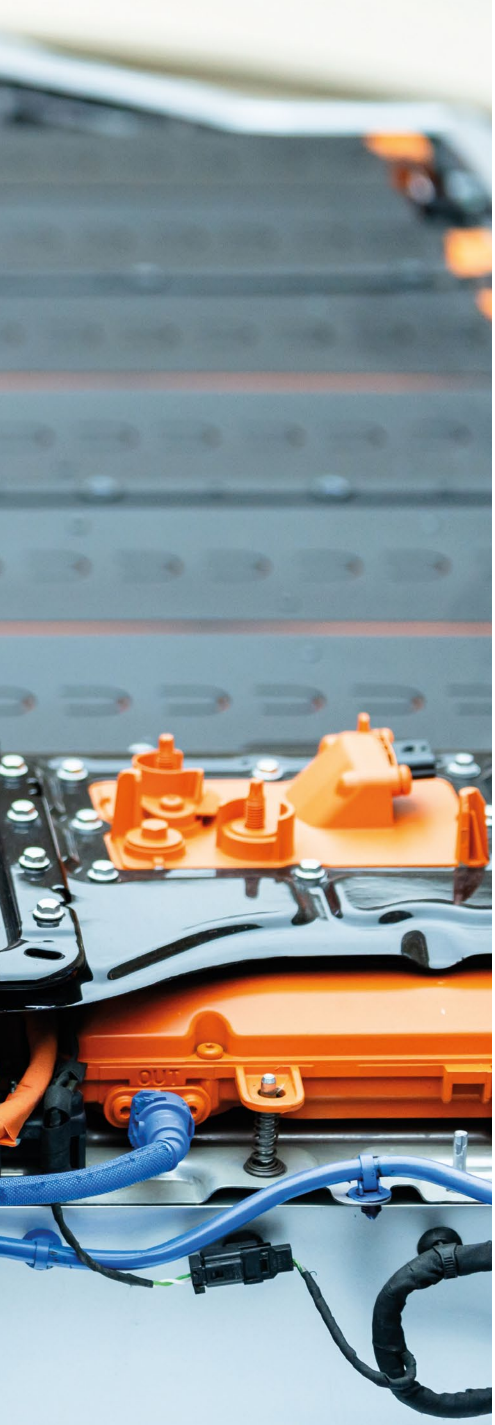
Optimizing Lithium-ion Battery Longevity with Foam Compression Pads

In the construction of lithium-ion batteries, the design of the compression pads has a significant influence on the long-term performance of the battery system. Rogers explains which factors are particularly decisive in the selection of suitable materials and how these can be taken into account.



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WRITTEN BY

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Lithium-ion (Li-ion) batteries are integral to a wide range of applications, including Battery Electric Vehicles (BEVs) and renewable energy storage systems. As the demand for these batteries continues to grow, advancements in both cell formats and chemistries are ongoing. Manufacturers are developing various designs – prismatic, cylindrical, and pouch formats – each optimized for specific use cases. Simultaneously, innovations in battery chemistry, such as high-nickel cathodes, silicon-based anodes and solid-state batteries, are enhancing energy density, efficiency, and safety.

Despite these technological advancements, one major challenge persists: ensuring the long-term performance and reliability of Li-ion cells throughout numerous charge-discharge cycles. A proven method to enhance the longevity of these cells is the application of external pressure, typically achieved through the use of compression pads placed between the cells. These pads apply a controlled force, helping to maintain the structural integrity and operational efficiency of the cells.

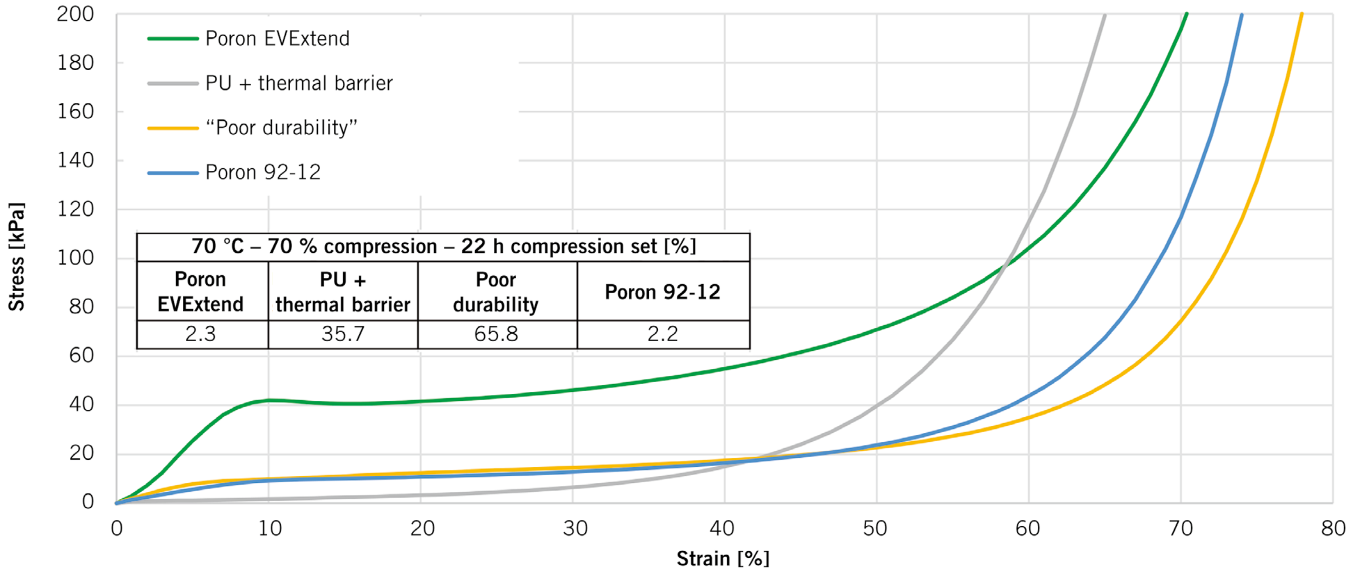
KEY FACTORS IN MATERIAL SELECTION FOR COMPRESSION PADS

Selecting the right material for compression pads is essential to applying the correct pressure to the cell throughout its lifecycle. Too much pressure can cause mechanical damage, shorten the cell's lifespan, and increase safety risks, while too little pressure can lead to inefficient energy delivery and reduced battery life.

Li-ion cells expand when charging and contract when discharging. The compression pad must adjust to these changes by compressing and decompressing while still applying a consistent force. Manufacturers typically recommend a specific pressure to be applied during installation (the so-called Beginning-of-Life (BOL) pressure) to ensure optimal performance during the cell's life.

The compressive behavior of the material is a key factor in material selection and is reflected in its compressive stress-strain curve. The material must provide the BOL force while also allowing for the cell's expansion during use. As the cell reaches its End-of-Life (EOL), irreversible swelling occurs due to the growth of the Solid Electrolyte Interphase (SEI) layer. At this point, the compression pad must continue to apply controlled pressure without exceeding levels that could damage the cell or its module enclosure.

To ensure the cell's longevity across multiple charge-discharge cycles, the compression pad must also be durable. There are a number of properties that are particularly relevant when it comes to evaluating long-term durability and performance: firstly the compression set resistance, secondly the stress relaxation, and thirdly the hysteresis. The compression set resistance refers to the pad's ability to return to its original thickness after being compressed. The stress relaxation describes the material's ability to maintain a consistent stress level under compression. It ensures that the compression pad can apply the correct pressure at the BOL, as well as maintaining optimal stress conditions throughout the battery's cycle life. The hysteresis describes how a material behaves differently when



70 °C – 70 % compression – 22 h compression set [%]			
Poron EVExtend	**PU + thermal barrier**	**Poor durability**	**Poron 92-12**
2.3	35.7	65.8	2.2

FIGURE 1 Compressive stress-strain curves of tested PU foams with durability test results (samples 50 x 50 mm, compression rate 5 mm/min) (© Rogers Corporation)

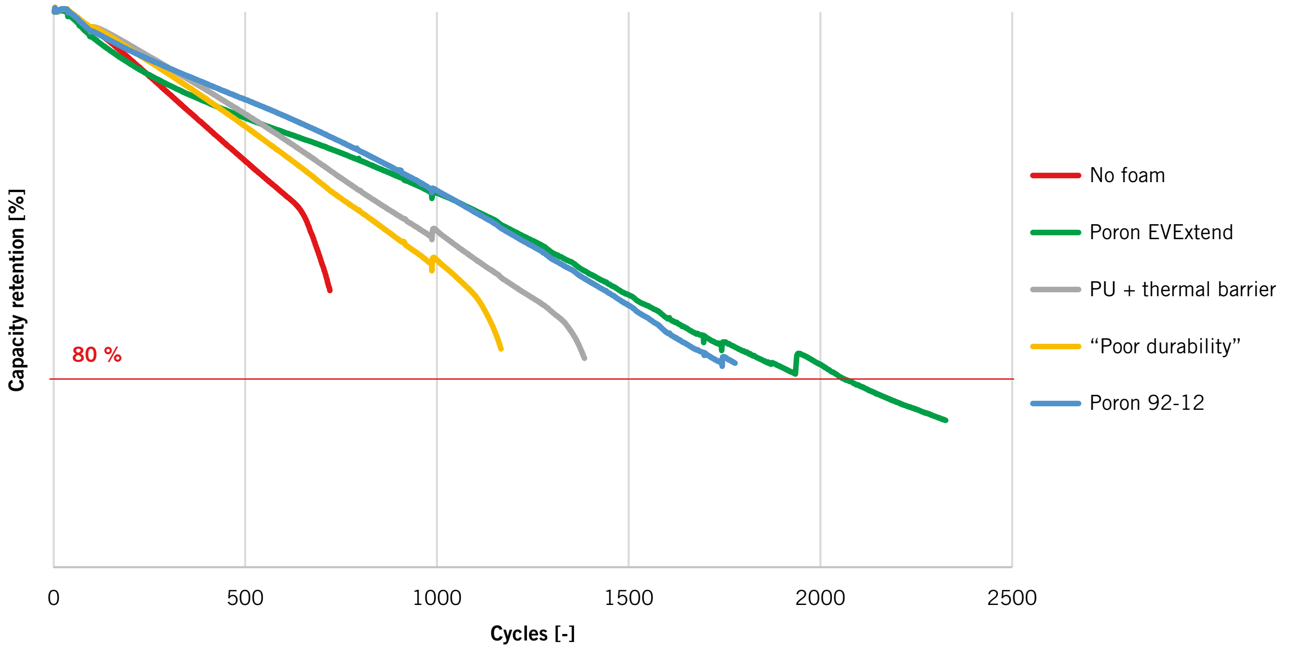
being compressed versus when being released. A pad with low hysteresis does not lose much energy during these cycles, which means it can apply steady, reliable pressure over time. This is especially critical in solid-state cells, where the electrodes and solid electrolyte need to stay in close, constant contact to allow charge to flow efficiently. If the pad loses pressure, even tiny gaps can disrupt this contact and hurt performance.

CASE STUDY: SINGLE CELL CYCLE TESTING

To assess the performance of different cell compression pad materials, a study was conducted using a 70-Ah NMC 811 pouch cell. The cell was subjected to continuous charging and discharging at a rate of 1C. The installation pressure (at BOL) was set at 15 kPa, as recommended by the cell manufacturer, and the cell was cycled until it reached 80 % of its original capacity.

Four Polyurethane (PU) foam materials with varying compression behaviors and durability were selected to assess their effect on capacity retention over time, **FIGURE 1**. The first material, Poron EVExtend (green curve in the diagram), is specifically designed to match the ideal compression behavior. It reaches the target BOL pressure

FIGURE 2 Capacity fade test results (© Rogers Corporation)



with minimal compression. During charging-discharging, the compression and decompression occur in the plateau region of the curve, ensuring stable pressure. The second material, a PU foam called Poron 92-12 (blue curve), is highly compressible but has a low curve slope. This means the material had to be compressed by about one-third of its thickness to achieve the target BOL pressure. The third material (yellow curve) has a compression behavior similar to that of the second Poron foam but displays an overall lower durability. The fourth material combines the Poron EVExtend foam with a compressible thermal barrier material (grey curve). This combination, often used in applications to mitigate Thermal Runaway Propagation (TRP), was included to determine how the thermal barrier affects cycling performance.

Durability of the PU foams was assessed using a compression set test under accelerated aging conditions (70 % compression at 70 °C). The two Poron foams showed minimal permanent thickness loss, indicating strong recovery. In contrast, the combination of Poron material and the thermal barrier showed a much higher compression set, primarily due to the barrier's limited recovery capability. The least durable PU foam retained only about one-third of its original thickness after compression.

These differences in durability were reflected in the cell cycling test results, where noticeable variations in capacity retention were observed, **FIGURE 2**. The best-performing material, Poron EVExtend, supported over 2100 cycles before the cell's capacity dropped to 80 %. This represents an increase in lifespan of about 200 % compared to a baseline test where no foam pad was used and the cell was allowed to expand and contract freely. When the same Poron EVExtend foam was combined with a thermal barrier, the number of cycles dropped to fewer than 1400, showing that the thermal layer negatively affected performance. The least durable foam material resulted in around 1150 cycles before reaching the 80-% capacity point.

During testing, force data were recorded to calculate the pressure differential (Δp) between the uncharged and fully charged states of the cell. This produced a unique curve for each compression pad material, **FIGURE 3**. A flatter curve – or lower slope – indicates better performance, showing that the foam maintains more consistent pressure throughout the charge-discharge cycles. Keeping the cell operating within this flatter region is important for maximizing capacity retention.

Three factors can cause Δp to increase quickly, reducing the effectiveness of the compression pad. These are foam thickness, poor compression set and unsuitable compressive stress-strain curve:

- If the foam is too thin, it cannot properly absorb the cell's expansion. This results in excessive pressure and a higher Δp during cycling.
- If the foam does not recover to its original thickness after being compressed, it will not provide enough pressure when the cell contracts during the next discharge. This may not be an issue at BOL, when cell swelling and pad compression are minimal, but becomes more critical in mid-life to end-of-life stages as swelling is more pronounced.
- Using a material with an unsuitable compressive stress-strain curve can force the cell to operate in the steeper region of the curve too early. The cell will experience larger pressure differences during each cycle, which can lead to faster capacity loss.

DISASSEMBLY ANALYSIS

After the cycling test was completed, the PU foams were removed and their compression curves were measured again to compare them with the initial curves recorded before the test, **FIGURE 4** and **FIGURE 5**. For the best-performing materials, the post-test curves were slightly softer, which indicates that some stress relaxation occurred during cycling. Stress relaxation is particularly important as the battery approaches its EOL. At this point, the cell has experienced permanent swelling, which pushes operation into the steeper region of the foam's compression curve. This results in a higher pressure difference (Δp) during cycling. A moderate amount of stress relaxation in the foam can actually help by reducing the pressure buildup caused by swelling, leading to potentially extending battery performance toward the end of its service life.

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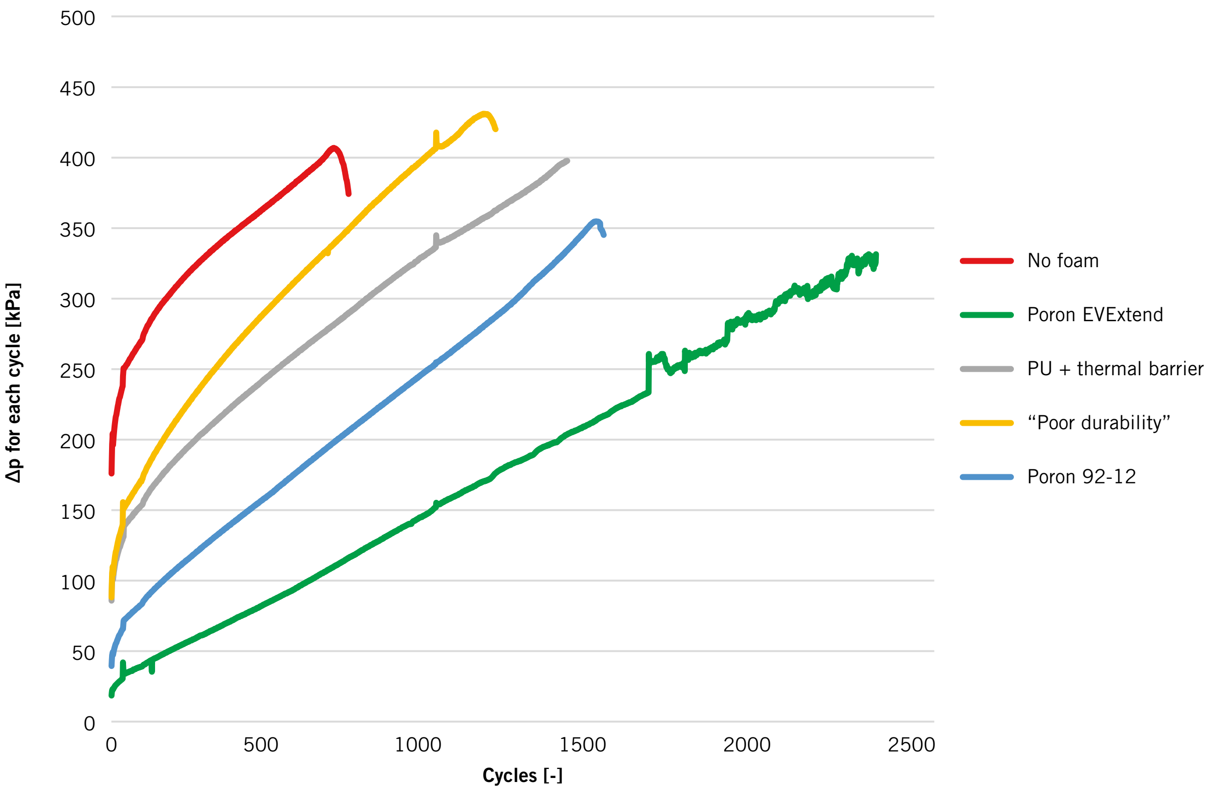
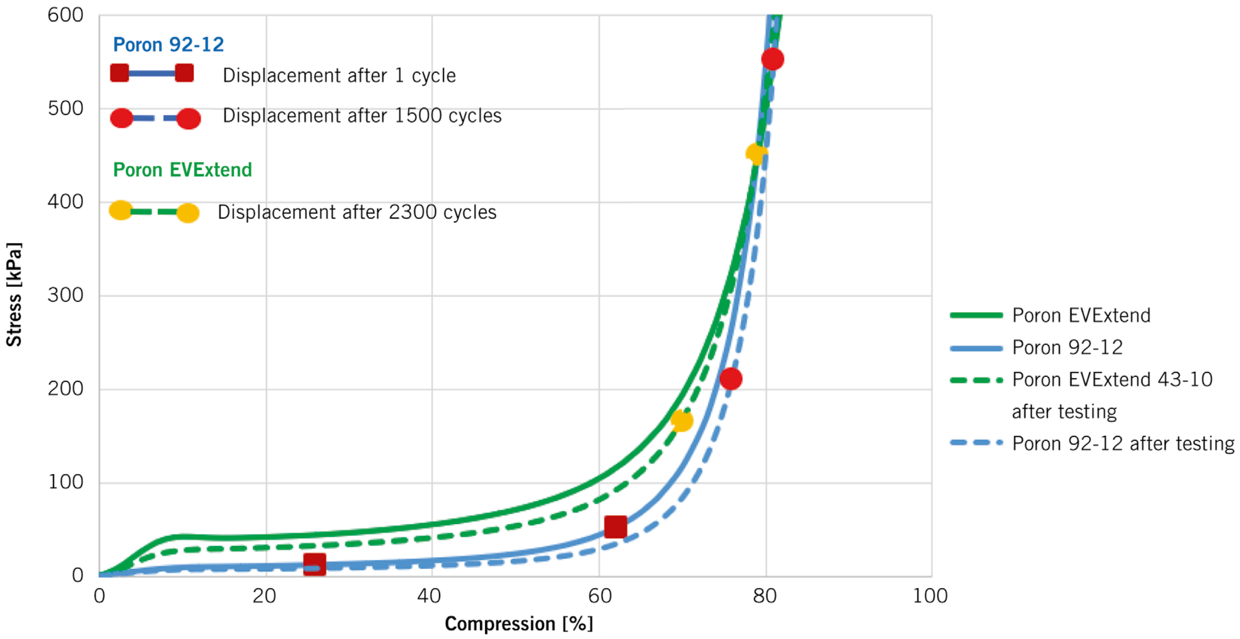


FIGURE 3 Pressure differential for all foam pad materials (© Rogers Corporation)

Integrating a Poron PU compression pad with a thermal barrier has a significant impact on the overall stress-strain response. Specifically, the addition of the thermal barrier changes the shape of the compression curve. If the thermal barrier has poor compression set resistance, the plateau region of the curve becomes much shorter. As a result, the cell moves into the steeper part of the compression curve after fewer cycles, causing increased pressure differentials (Δp) during operation.

FIGURE 4 Best performers: relaxed compression curves after the test and operation path BOL/EOL (© Rogers Corporation)



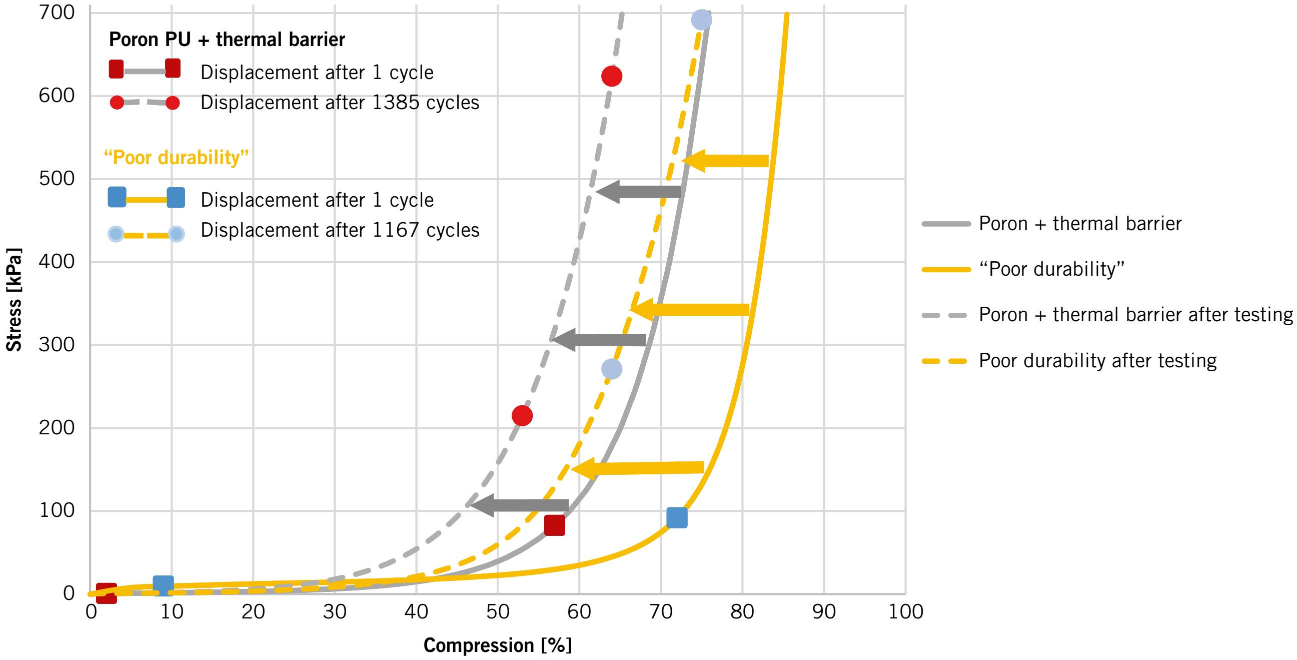


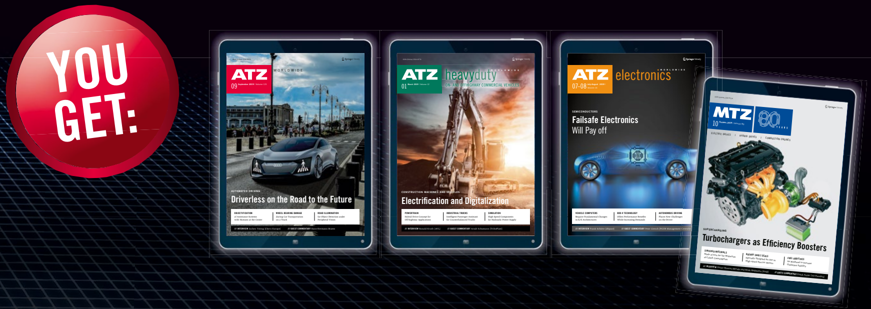
FIGURE 5 Worst performers: relaxed compression curves after the test and operation path BOL/EOL (© Rogers Corporation)

CONCLUSION

This study emphasizes the important role of compression pads – not just as simple spacers, but as active components that directly affect cell performance, safety, and lifespan. The results show that choosing the right compression material, like Poron EVExtend, can significantly improve battery durability by maintaining consistent pressure over thousands of charge and discharge cycles. On the other hand, materials with poor compression resistance, weak stress relaxation, or poorly matched compression characteristics can speed up performance decline, especially as the cell nears its end of life.

Additionally, while thermal barrier materials can enhance safety in thermal runaway situations, their use must be carefully balanced with mechanical performance needs. If the thermal layer negatively impacts the stress-strain behavior, it could unintentionally harm the cell's long-term health.

In the end, selecting the right compression pad is not just about achieving the desired pressure at the start of the cell's life. It involves understanding how the pad will perform over time, especially under aging, swelling, and changing internal pressure conditions. As battery systems become more advanced and demand higher reliability, engineers and designers should treat compression material selection as a key design choice that directly impacts the battery's lifespan, safety, and total cost of ownership. Optimizing battery lifespan therefore starts with managing pressure, and managing pressure starts with the right foam.



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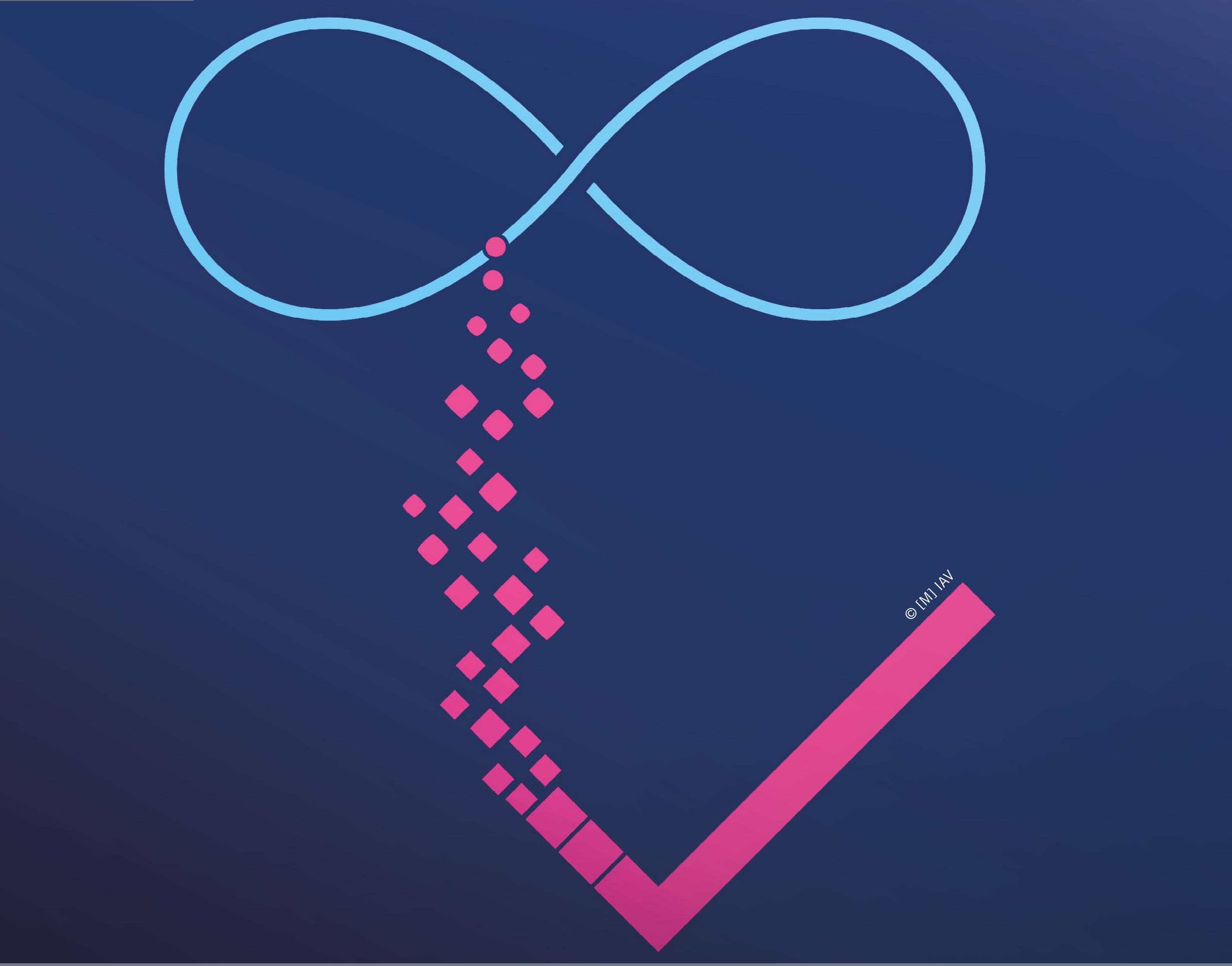

Agile Development Methodologies for Safety-critical Powertrain Systems

In the realm of safety-critical software systems, ensuring both functionality and compliance with stringent safety standards is paramount. IAV is increasingly using agile development methods for this task. The article explores the key components, including requirements specification, architecture design, testing, change tracking, and complexity management.

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In recent years, there has been a significant increase in the adoption of agile development methodologies for safety-critical software, driven by the need to accelerate time-to-market, reduce costs, and enhance product quality. In the agile development approach, software systems are constructed through a series of increments, with each increment typically lasting three to four weeks. These short, repetitive increments allow for continuous improvement and frequent delivery of functional software.

At IAV, the use of a shared model between system and safety engineers promotes communication and collaboration, reduces misunderstandings and ensures that all stakeholders have a clear understanding of safety implications throughout development. For every feature developed, a so-called change view in Enterprise Architect software documents changes to requirements, design, and test specifications. Utilizing models for generating documentation and compliance trails for ISO 26262 not only streamlines the documentation process but also enhances the overall safety management framework.

METHODOLOGY FOR SAFETY-CRITICAL ASPICE-COMPLIANT SOFTWARE DEVELOPMENT

The development process was adapted to maintain agility, manage complexity, and ensure compliance with safety standards. The approach to developing safety-critical software uses feature-based development and employs planning for software releases spread over multiple so-called sprints which involve a set of analysis and implementation sprints.

In order to effectively integrate agile methodologies in safety-critical software development, two essential prerequisites must be established. Firstly, a robust quality management system is required, with Aspice Level 2 serving as a suitable benchmark for process maturity in automotive software development. Secondly, a functional safety management system and a suitable development approach for safety-critical software must have been implemented beforehand [1]. Both these prerequisites are satisfied by the established safety culture and quality as well as functional safety management systems at IAV.

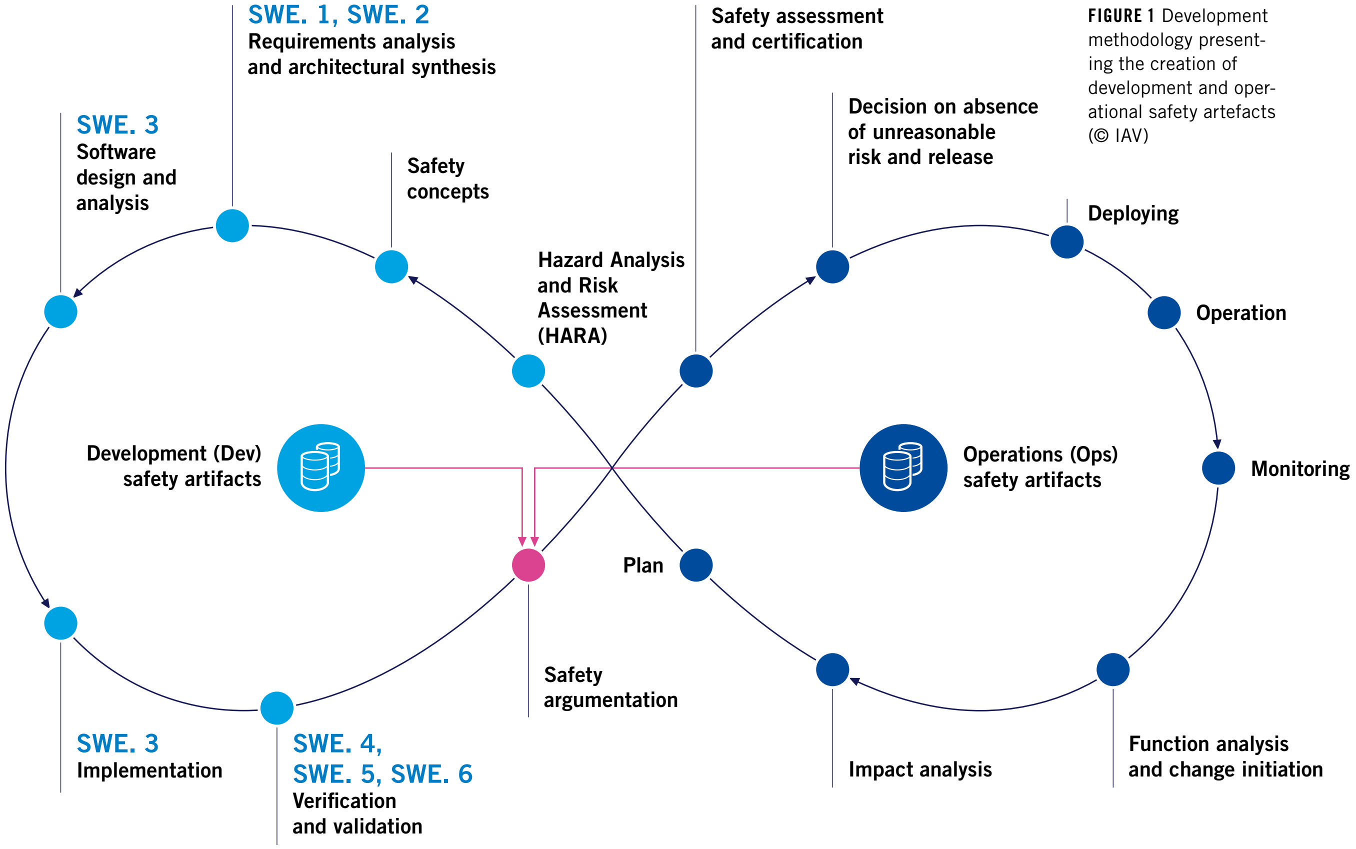
SWE. 1, SWE. 2
Requirements analysis and architectural synthesis
SWE. 3
Software design and analysis
Safety concepts
Hazard Analysis and Risk Assessment (HARA)
Safety assessment and certification
Decision on absence of unreasonable risk and release
Deploying
Operation
Monitoring
Development (Dev) safety artifacts
Operations (Ops) safety artifacts
Plan
Safety argumentation
SWE. 3
Implementation
SWE. 4, SWE. 5, SWE. 6
Verification and validation
Impact analysis
Function analysis and change initiation

FIGURE 1 Development methodology presenting the creation of development and operational safety artefacts (© IAV)

FIGURE 1 presents the main development and operational stages in the methodology in line with ISO 26262:2018 standard with work products developed as per Aspice requirements. In addition to the processes for developing safety-relevant artifacts, the following seven aspects are among the core elements of the development methodology:
- impact analysis
- analysis sprint
- safety-centric backlog
- change management and tracking
- implementation sprint
- verification, confirmation and safety reviews
- release management.

These terms originate from the process environment of agile development and are explained below.

Before implementing changes, an impact analysis assesses how changes will affect both functional and safety software. Periodic impact analysis is done on this backlog at the start of every release. Any change in the system or its boundary conditions is studied during the impact analysis – this analysis is repeated cyclically for each release (eight-to-ten-week cycle). Two weeks before the so-called requirements freeze (after which changes to the requirements can no longer be taken into account), a new evaluation is carried out by resending a questionnaire to the stakeholders.

After the requirements freeze, a two-week analysis sprint takes place in which the effects on the individual elements of the safety lifecycle are determined. Further analyses are then carried out as part of the ticket processing to define the detailed adjustments of the individual work products.

The product backlog includes not only functional requirements but also safety-related tasks such as formulation of technical safety requirements, architectural synthesis and test specification development. These tasks are prioritized alongside other user stories in the so-called safety-centric backlog to ensure that safety is an integral part of the development process [2]

For all identified changes that affect the source code, formal Change Requests (CRQs) are generated and tracked in the change management and tracking step using the software tool Jira. In addition to facilitating implementation and summarization via the change view in Enterprise Architect, these CRQs undergo a rigorous commercial and technical approval process.

The implementation sprint is focused on development and testing activities, encompassing verification and qualification processes. Additionally, it ensures the creation and maintenance of comprehensive documentation, as well as the traceability of all developed artifacts.

The change tracking (verification, confirmation and safety reviews) is carried out via Jira (epics with subtasks for each work product). The reviews are supplemented by a safety audit and safety assessment according to ISO 26262:2018.

The release approval process for safety-relevant software development via release management employs agile methodologies to ensure compliance with the defined safety concept while effectively mitigating hazards. This process begins with an examination of the validation basis from previous software releases, assessing whether the concept has been fulfilled as validated in prior projects. It incorporates a comprehensive impact analysis to confirm the validity of implemented features and identifies any outstanding issues related to hazard violations.

Furthermore, the process delineates the minimum required software maturity level, the necessary test coverage, and limitations for integrating prototype components into the system. The release approval also specifies usage restrictions associated with prototype parts, detailing potential impacts on overall system safety. This culminates in a thorough evaluation that includes remarks on safety relevance and operational controls, which must be executed by trained drivers. By leveraging iterative development cycles and continuous feedback, this approach ensures that safety considerations are embedded throughout the software lifecycle, aligning with agile principles while adhering to stringent functional safety standards such as ISO 26262:2018.

SOLUTIONS AT THE INTERSECTION OF AGILE, ISO 26262 AND ASPICE

The integration of agile methodologies in safety-critical software development presents unique challenges, particularly in balancing iterative planning with the necessity of meeting strict release deadlines. A feature-based development approach is

Process group of Aspice	Description
System requirements analysis (SYS. 2)	Contains system requirements describing how the system should behave.
Software requirements analysis (SWE. 1)	Contains software requirements derived from the system requirements. Plausibility-based parameters generated within the transmission software are used here.
Software architectural design (SWE. 2)	Defines the software architecture, including modules, interfaces, and data flows. This serves as the basis for detailed software design.
Software detailed design (SWE. 3)	Describes detailed software design along with software modules and their interfaces.
Software implementation (SWE. 3)	C-language implementation, based on detailed design.
Software unit verification (SWE. 4)	Verification of individual software modules (unit tests). The module test specifications are derived from the detailed design (SWE. 3).
Software integration (SWE. 5)	Static testing for resource utilization and data flow verification between architecture/design and code. Additionally, testing of dynamic behavior on the HiL test bench.
Software qualification (SWE. 6)	Testing the entire software against the specified requirements. The SWE. 6 tests are performed on the HiL test bench and use both transmission internal measurement and calibration parameters as well as external parameters, e.g., from the HiL model.
System integration and qualification (SYS. 5)	Final qualification at the system level to ensure that it meets the original requirements (SYS. 2). SYS. 5 tests are performed on the HiL test bench and use model variables. Internal variables are used only in exceptional cases when manipulation outside the system boundaries is not possible.

TABLE 1 Aspice process groups (© IAV)

followed, based on release cycles with four to six sprints. This approach is supported by a combination of so-called Scrum ceremonies.

Planning is divided into two phases. Initial (general) planning focuses on prioritizing features based on requirements and other aspects. Impact analysis outcomes provide rough effort estimations to preselect features for the current release cycle. During fine planning, a detailed division into tasks, scheduling and allocation of responsibilities takes place, supported by findings from the analysis sprints.

The roles of the so-called Product Owner, Safety Manager, and Agile Master are pivotal in the context of agile methodologies for safety-critical software development [2]. The Product Owner collaborates closely with the Safety Manager to create and maintain the product backlog, ensuring that it reflects both business value and safety requirements. The Product Owner prioritizes features based on customer needs while integrating safety considerations to align with standards such as ISO 26262. This collaboration ensures that safety requirements are seamlessly embedded into the development process.

The use of Continuous Integration (CI) and Continuous Testing (CT) enables early detection and resolution of errors [3], performance issues, and compliance risks. In addition to meeting the standard requirements, the tools used must be assessed for tool confidence level and, if necessary, qualified according to ISO 26262:2018 Part 8.

During these sprints, the developed test cases are validated on at least one derivative vehicle to ensure applicability and performance. At the conclusion of each release, comprehensive test campaigns are executed across all relevant testing levels (SWE.4, SWE.5, SWE.6, and SYS.5). Module, integration and software qualification tests as well as quality assurance (QAC) tests are carried out with each release in the form of a test campaign to comprehensively validate the security functions. However, in the case of serious or safety-critical errors, it may be necessary to suspend software release until the error is immediately corrected.

EXAMPLE USE CASE

In the following use case, a safety functionality was implemented for a dual-clutch transmission with a hybrid module. A distinctive feature of this transmission is the freewheel mechanism in first gear. The first sub-transmission has only one gear actuator. The first gear is mechanically always engaged, but due to the freewheel, it is only effective when no higher gear (third or fifth gear) is engaged. During production of the transmission, a basic clutch calibration is performed. In this process, the so-called kiss points of the clutches, the synchronization positions, and the gear actuator engagement paths are determined. For this calibration to run correctly, all gears must be disengaged. Otherwise,

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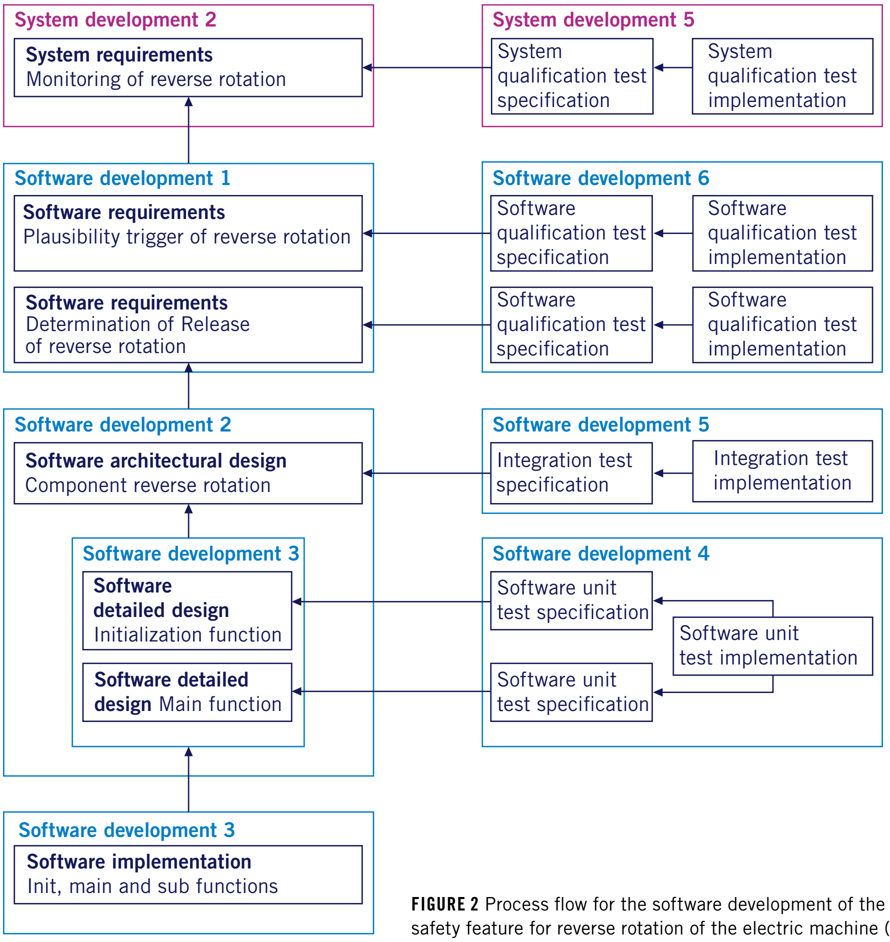
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Software detailed design Main function
Software development 4
Software unit test specification
Software unit test implementation
Software unit test specification
Software development 3
Software implementation
Init, main and sub functions

FIGURE 2 Process flow for the software development of the safety feature for reverse rotation of the electric machine (© IAV)

the vehicle could attempt to drive against the parking lock with first gear engaged and clutches closed.

To prevent this, the electric motor must be operated in the reverse direction during the basic calibration. This keeps the freewheel open, and first gear remains inactive. However, the kiss point determination of the clutch between the electric motor and the dual-clutch transmission must again be performed in the normal direction of rotation. Before and throughout the entire calibration process, the direction of rotation of the electric motor must be continuously monitored. To meet the safety goals – such as avoiding unintended movements in the wrong direction or undesired delays – the reverse rotation of the electric motor must only be allowed during basic calibration and not during normal driving operation (monitoring of reverse rotation).

The safety function (SE2), classified according to Asil B, must ensure that the reverse rotation of the electric motor via the CAN interface can only be requested when the vehicle is stationary and the parking lock is engaged (determination of release of reverse rotation), and that the request for reverse rotation is confirmed by the calibration procedure in at least two consecutive measurement cycles (plausibility trigger of reverse rotation). The implementation of the feature is split across the different Aspice process groups, **TABLE 1**.

The implementation of this functionality through the software development process is illustrated in **FIGURE 2**. The diagram is divided into several blocks that represent the relationships between different development and testing phases in the security-relevant software development lifecycle.

CONCLUSION

Developing safety-relevant software systems requires a structured and rigorous approach to ensure both functionality and compliance with safety standards. The approach by IAV not only improves the quality and safety of the final product but also increases efficiency and traceability throughout the entire development lifecycle. Currently, the focus is on feature-driven development and the analysis of issues that arise during vehicle testing and commissioning. This approach could for data-based monitoring in vehicle operations are being expanded.

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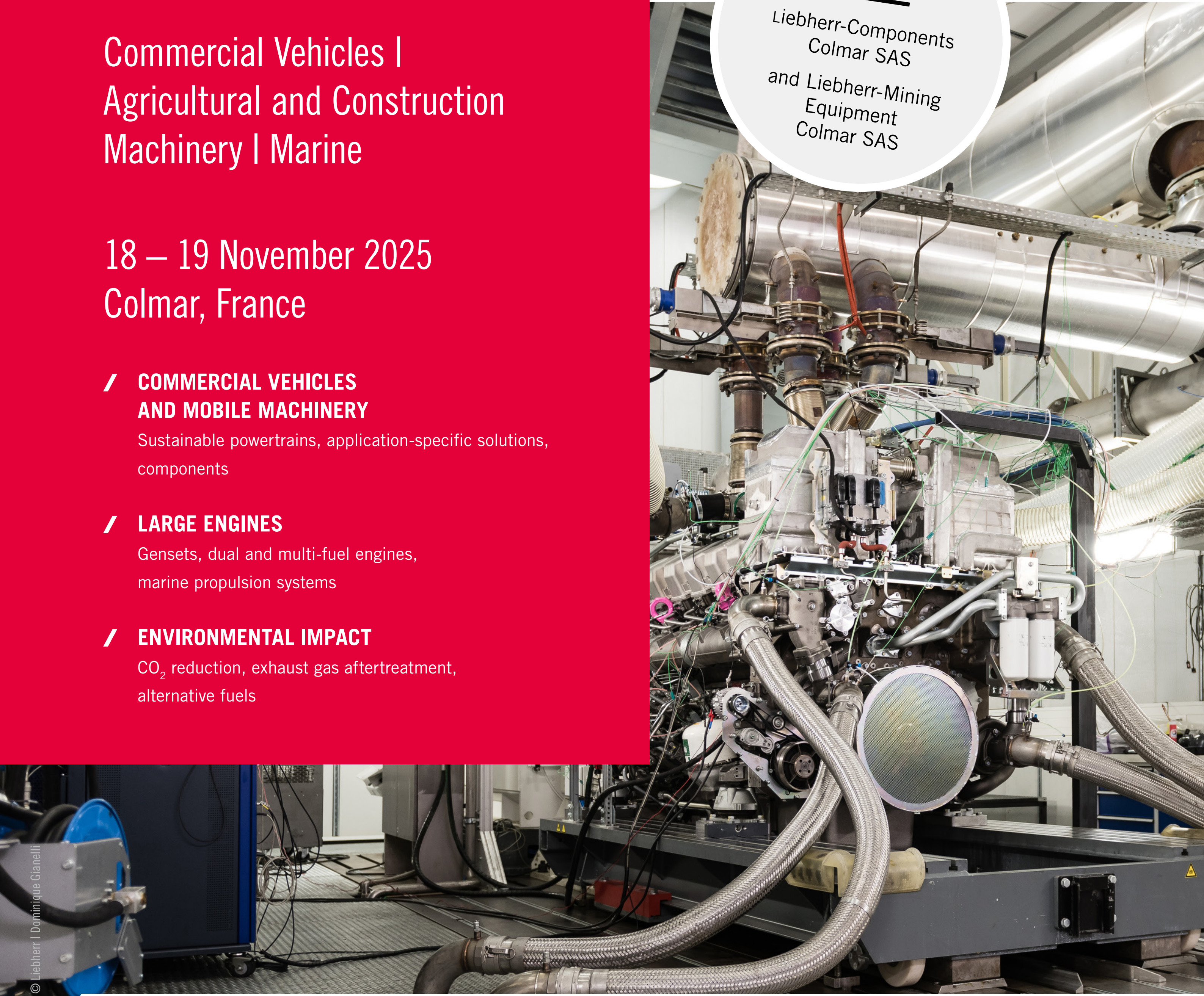

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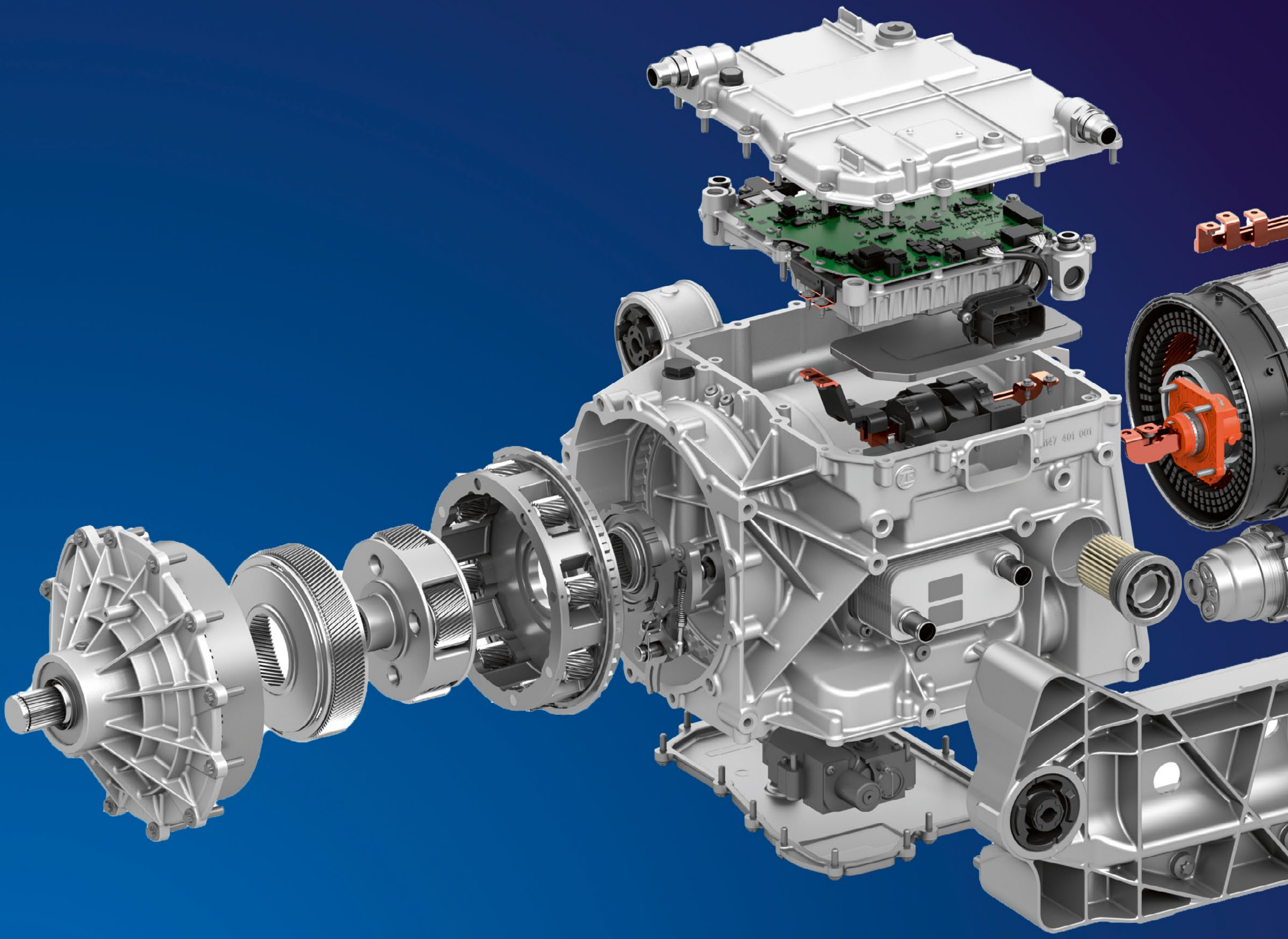
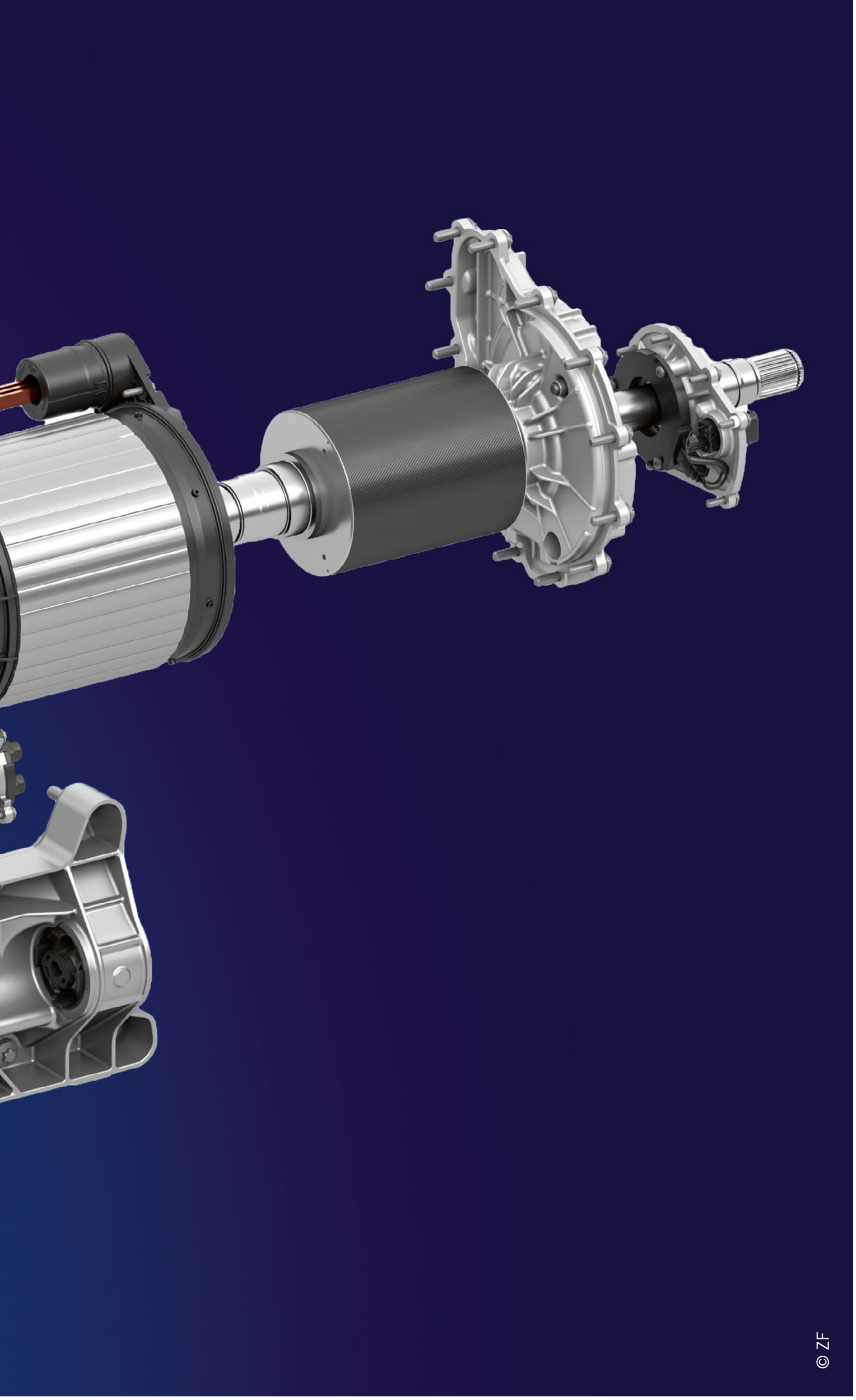


Modular Platform Concept for 800-V Electric Drives

With its so-called Select platform, ZF has designed a modular concept for 800-V electric drives that promises shorter development times, faster time-to-market, and greater flexibility in production. Since it offers the possibility of integrating new individual components, the platform can also be used to implement technical innovations in electric drives in the future.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From a global perspective, the market for vehicles with electric drives is growing dynamically. Nevertheless, there has been a high degree of differentiation in the drive configurations for the respective passenger car platforms in recent decades. Depending on the application and market positioning, there are different requirements, which is why a variety of electric drive technologies are used in vehicles. Technology providers for electric drive systems for passenger cars are therefore faced with a twofold basic problem. On the one hand, they must master different technologies to offer manufacturers a drive solution tailored to their application on the development side. On the other hand, it must also be possible to industrialize this within the increasingly tight deadlines and cost expectations of the manufacturers. The latter requires a high degree of standardization of the solutions.

To combine high-level application-specific individualization with strict standardization, ZF is taking the path of focusing and modularization. The aim is to be able to develop an overall system within selected performance classes that is made up of modular components (building blocks) for electric motors, power electronics, reduction gears and, finally, software. In the so-called Select platform developed by ZF, these building blocks are defined and in turn created as sub-modules to ensure further flexibility in the range of functionalities.

After analyzing the market for electric primary and secondary drives, the focus was placed on a specific market segment that ZF will serve in the future with the new platform. ZF is a supplier of electric drives for 800-V architectures

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in the power range between 200 and 300 kW. This segment is dominated by the demand for high torque and power density, which ZF can serve with its experience in Permanent magnet Synchronous Motors (PSM) and Asynchronous Motors (ASM) technologies, current innovations in the Separately Excited Synchronous Motor (SESM) area and its transmission expertise.

PLATFORM AND PRODUCT DEVELOPMENT IN PARALLEL

Within the defined segment, ZF focused on specific and customer-specific drive axle concepts for the development of its Select platform. The development processes of the specific axle concepts as well as the platform and its modular components and Key Performance Indicators (KPIs) were interlinked. The concepts are therefore both the starting point and result for the development of the platform and include the following:

– a primary drive that can be configured for the power range between 150 and 300 kW and a torque between 3500 and 5500 Nm with a focus on efficiency in the Worldwide harmonized Light vehicles Test Cycle (WLTC), power density, overall height and continuous power
– a concept suitable as a secondary drive for the power range between 100 and 200 kW and 2000 to 3000 Nm with a focus on minimized drag power and high power density
– a secondary drive for high-performance applications between 200 and 250 kW and a significantly higher continuous output compared to ASM concepts as well as a focus on WLTC efficiency, minimized drag power and power density.

The systems to be developed based on the platform must fulfill the requirements of all global test cycles (WLTC, China Light-duty vehicles Test Cycle (CLTC), US06, EPA Highway Fuel Economy Test (HWFET), EPA Urban Dynamometer Driving Schedule (UDDS)).

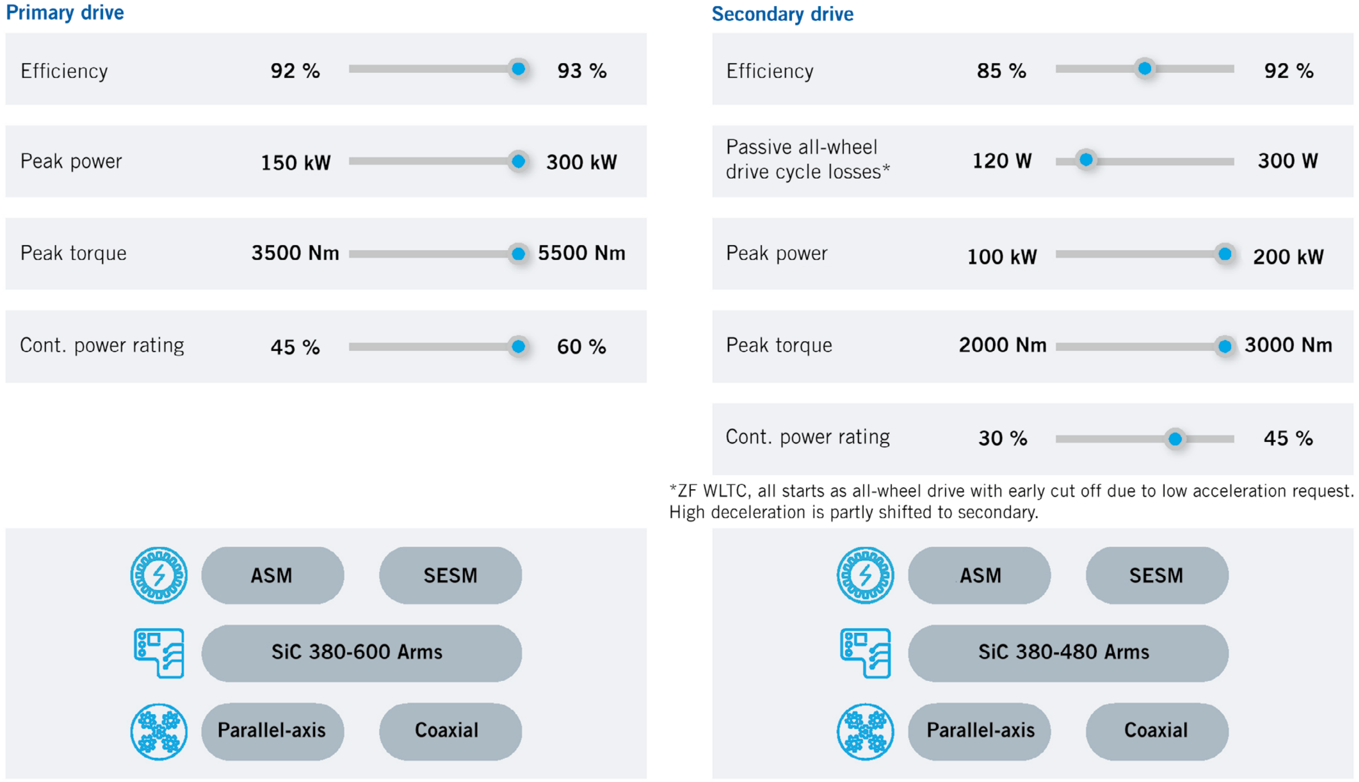
VISUAL REPRESENTATION OF THE REQUIREMENTS

For the platform, all defined requirements have been brought together in a so-called slider overview, **FIGURE 1**. This visual appearance illustrates the high level of flexibility that is a key advantage of the modular concept. The individual components used are essentially responsible for the variance of the desired features. The overall system guarantees the integration capability of the individual components and is therefore also open to the future; the platform is continuously being supplemented with further technology solutions that are still under development.

OVERALL SYSTEM AND BUILDING BLOCKS

The overarching goals of faster market readiness and flexible production require strict interface definition and rigorous requirements management, starting with the system concept and cascading down to the individual components, **FIGURE 2**. One principle of the new platform is to be able to integrate innovations quickly. Interfaces, assembly directions, and technologies were agreed together with production and development in such a way that production remains lean and scalable despite variance. This also creates the basis for a high scalability in

FIGURE 1 Platform for flexible adaptation to market requirements (© ZF)



Primary drive

Efficiency	92 %	93 %
Peak power	150 kW	300 kW
Peak torque	3500 Nm	5500 Nm
Cont. power rating	45 %	60 %

Secondary drive

Efficiency	85 %	92 %
Passive all-wheel drive cycle losses*	120 W	300 W
Peak power	100 kW	200 kW
Peak torque	2000 Nm	3000 Nm
Cont. power rating	30 %	45 %

*ZF WLTC, all starts as all-wheel drive with early cut off due to low acceleration request. High deceleration is partly shifted to secondary.

terms of units and a transparent presentation of one-off and unit costs, which is also important for marketing the building blocks as individual components.

ELECTRIC MOTOR PLATFORM

When using the electric motor, ZF can adjust the levers of efficiency, power density, torque density, costs, and sustainability (for example by dispensing with (heavy) rare earths) by selecting the rotor technology and its design. In addition to the proven PSM and ASM technologies, ZF innovations such as the so-called I2SM rotor (In-Rotor Inductive-Excited Synchronous Machine) and a carbon-taped rotor (rotor with carbon bandage) are planned.

All rotor concepts within the so-called em:Select modular system are combined with a standardized stator, **FIGURE 3**. It can be produced in diameters of 215 to 245 mm and in active lengths between 80 and 160 mm. Innovations in industrial production, which are also part of the new development, allow for an optimal selection of sheets. With the so-called core elastic approach, a further development of torque transmission via press fit is used. The aim is to keep the pressure constantly low over the entire operating temperature range in order to minimize the iron losses caused by residual stress in the stator laminations. In stator production, ZF is using a new and innovative winding process called Flexpin for the first time, which makes the number of layers and windings more flexible, enables a thinner wire coating, and allows shorter winding heads on the welding side.

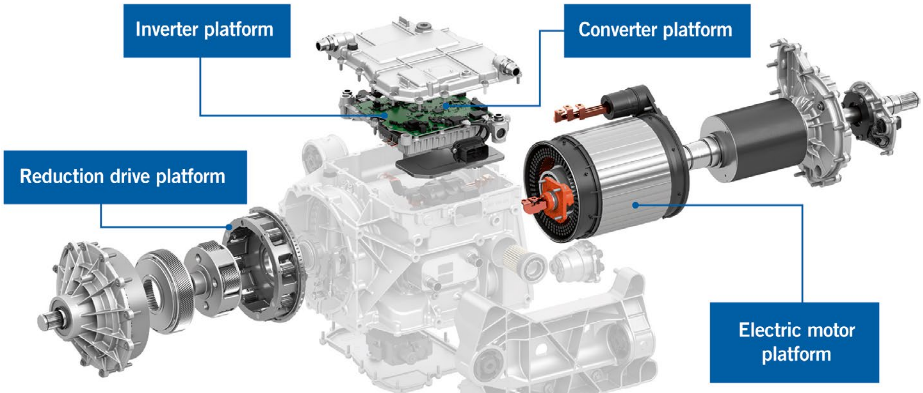
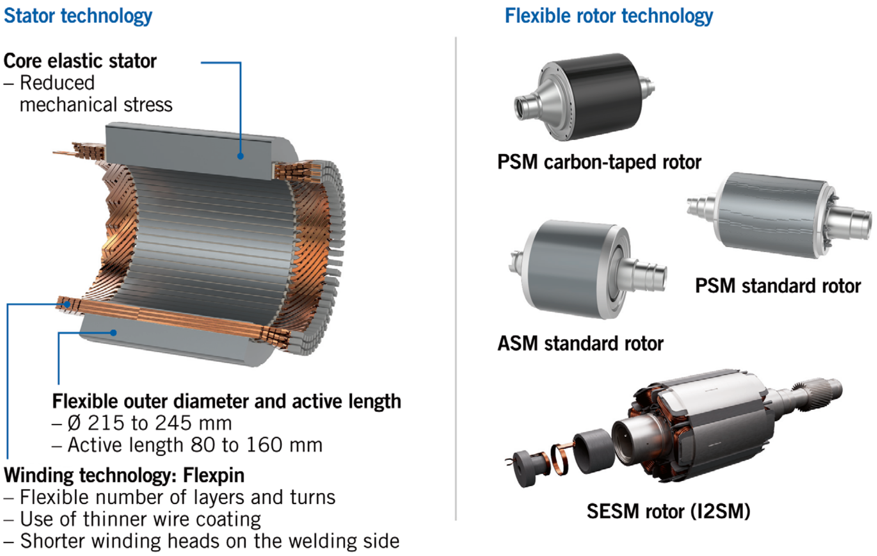

Inverter platform
Converter platform
Reduction drive platform
Electric motor platform

FIGURE 2 Fast integration thanks to clearly defined interfaces between the overall system and individual components (© ZF)

With regard to the portfolio of rotor technologies, only the I2SM, a separately excited rotor technology, will be discussed in the following, even though the em:Select modular system contains many other solutions. With the I2SM, it was possible to develop a magnet-free electric machine that operates at the level of a PSM in terms of performance. The inductive transformer enables 40-A excitation current and up to 10-kW excitation power on the rotor shaft. An integrated oil cooling system developed by ZF is responsible for the significantly improved continuous performance, which achieves current PSM targets and thus outperforms existing SESM solutions. In terms of power and torque density, the I2SM rotor also outperforms other magnet-free rotor technologies by 30 %, as it achieves a higher copper filling thanks to plug-in coils.

FIGURE 3 Standard stator and rotors as building blocks of the electric motor platform (© ZF)


Stator technology
Core elastic stator
– Reduced mechanical stress
Flexible outer diameter and active length
– Ø 215 to 245 mm
– Active length 80 to 160 mm
Winding technology: Flexpin
– Flexible number of layers and turns
– Use of thinner wire coating
– Shorter winding heads on the welding side
Flexible rotor technology
PSM carbon-taped rotor
PSM standard rotor
ASM standard rotor
SESM rotor (I2SM)

INVERTER DEVELOPMENT

The 800-V inverter technology developed for the Select platform is responsible for a high power density (> 80 kW/l) and enables scalable, sustainable and efficient solutions. The peak efficiency is 99.6 %. The modular sub-assembly system in:Select can switch currents of up to 600 A Root Mean Square (RMS). At the same time, the inverter takes up 30 % less installation space. The discrete design of the power switching modules allows multi-sourcing when selecting semiconductor suppliers and reduces the risk of supply bottlenecks. Scaling the current and changing the semiconductor supplier is possible without changing the software and can be done via the application.

REDUCTION GEARBOX

Space and weight-optimized reduction gears with stacked planetary gears are an important lever when high torque density is required. Both axially parallel and coaxial designs are available as building blocks within the rd:Select

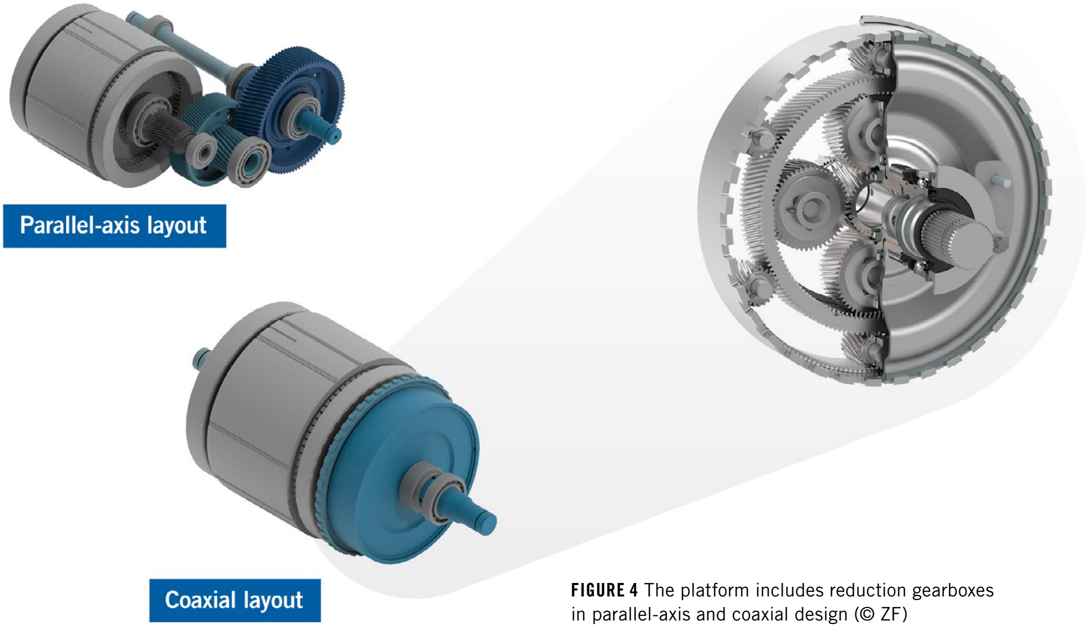


FIGURE 4 The platform includes reduction gearboxes in parallel-axis and coaxial design (© ZF)

modular system, **FIGURE 4**. In the coaxial design, which also integrates the differential function, ZF makes use of its comprehensive planetary gearbox expertise, which originates from the development of automatic transmissions. A reduction of up to 70 mm length in the Y-direction and weight savings of more than 5 kg can be achieved compared to axially parallel reduction gears.

CONVERTER TECHNOLOGY

The converter is a key component for focusing on 800-V architectures. ZF's converter portfolio has a modular structure. Certain functionalities were defined within the co:Select modular system, which can then be expanded and scaled as required using hardware or software.

The concept integrates bidirectional Onboard Charging (OBC, Alternating Current (AC)), boost charging (Direct Current-Direct Current (DC/DC) for 400-V charging stations and 800-V batteries, high-, low-, and middle-voltage access for the on-board power supply and Vehicle-to-Load (V2L) functionality in a single housing. This converter platform already achieves a high level of integration – with the aim of expanding this to full functional integration soon. The basic software is configured in such a way that further modules can be connected to form an integrated (X-in-1) solution.

APPLICATION DEVELOPMENT AS PROOFPOINT AND BENCHMARK

Parallel to the development of the Select platform, three specific applications have already been developed on its basis, plus corresponding benchmark tests. The applications are a coaxial primary drive (based on a PSM with an output of 300 kW and 5500 Nm torque), a parallel-axle secondary drive (based on an ASM with 200 kW output and 3000 Nm torque), and a significantly sportier variant of a parallel-axle secondary drive based on the I2SM.

The first two variants were built and tested independently by customers. This makes it possible to compare both the performance data and the production costs based on the bill of materials and production concept. To ensure the fairest possible comparison, a Chinese manufacturer of battery electric vehicles was used as a benchmark in an internal comparison and the framework conditions were adapted to the production location. In this Best Practice Indication (BPI) comparison for the primary drive, the ZF solution is 15 % more cost-effective and, at the same time, achieves better values for efficiency, peak torque, installation space, and weight.

A similar matrix was used to test the application of the secondary drive in comparison with another Chinese automobile manufacturer. This resulted in similarly positive results on the cost side. In terms of technical performance indicators, the ZF solution scored particularly well in terms of low drag torque and maximum power.

The third application, the sporty variant of an axially parallel secondary drive based on the I2SM, provides an output of 250 kW and 3500 Nm of torque. Internal tests have shown that thanks to its very high active efficiency and high continuous performance, it requires significantly fewer compromises when it comes to reconciling low drag losses, high performance, and low engagement delay. In contrast to similar high-performance approaches with PSM machines, it does not require a disconnect function.

SUMMARY AND OUTLOOK

ZF's Select platform for electric drives consists of a highly integrative overall system and flexible modular components that are optimally matched to each other and to market requirements. In this way, important strategic goals can be achieved, such as shorter development times and faster market maturity, fast and easy industrialization as well as flexible scaling. The platform enables seamless integration of future component innovations.

Electric Mobility

E-mobility is a key component in sustainably reducing the CO_2 footprint. Today's electric cars have the same range as comparable gasoline-powered cars. However, there is still room for improvement in terms of renewable power generation and storage, as well as grid infrastructure. In addition, vehicles must become more affordable for end customers if e-mobility is to become mainstream. Here are the latest links to the cross-media focus on Springer Professional.

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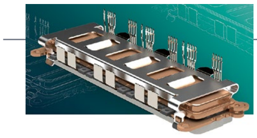

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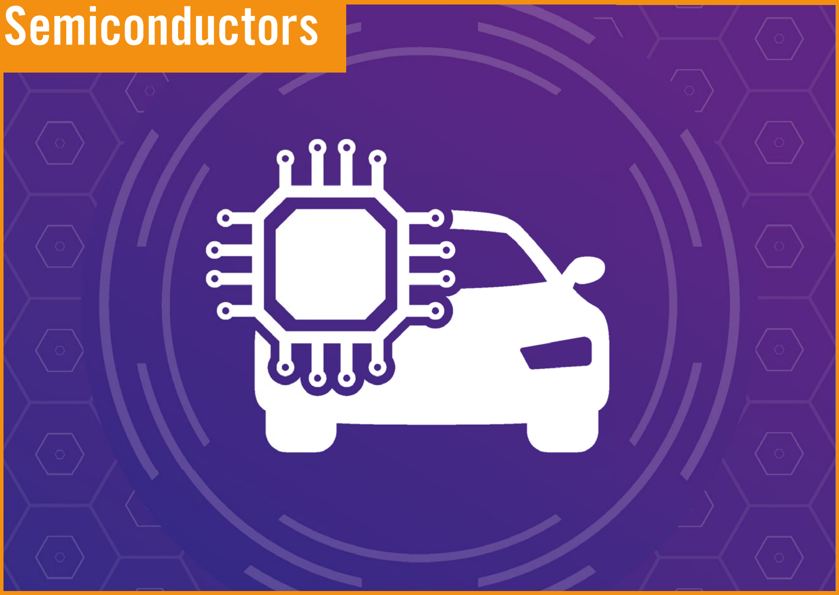
COVER STORY

Semiconductors



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Combining optical technologies with electronic structures is already clearly recognized in many areas as the way forward for semiconductor technology, even if this is not easy to achieve due to the relatively slow pace of development and the different manufacturing techniques used in electronics. This opens up new approaches "beyond Moore," which, due to extreme packing densities and the associated thermal problems of processors, seemed to be heading toward an absolute limit for semiconductor technology – a limit that has been pushed back again and again. In its contribution on the topic of sensor edge cloud for federated learning, Fraunhofer highlights a possible paradigm shift for computer architectures. These are based on neuromorphic computing using neural networks. The project includes the programmable chip architecture Senna with a 22-nm reference design. In an interview, Infineon highlights the future potential of Risc-V architecture, which is expected to be very promising for the automotive industry – the magic word here is open source. It remains to be seen to what extent open source is truly open and what the ecosystem of software and hardware that still needs to be created will look like. And, incidentally, it also remains to be seen how well it will perform in comparison to established worlds such as Arm or Nvidia.

20TH ANNIVERSARY

IN THE SPOTLIGHT

Charging Concepts for Battery-powered Trucks and Buses

DEVELOPMENT

Virtualization of Electric Powertrain Development for Improved Global Competitiveness

Hardened Structures for Secure and Scalable Security

Implementing Software-defined Vehicles Through General, Fundamental Architecture Models

THE HANSEN REPORT

News + Analyses

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Circular Software-defined Vehicles

Alongside global and geopolitical challenges, engineers and strategists in the automotive industry are currently focusing on two megatrends: Software-defined Vehicles (SDVs) and the Circular Economy (CE). In SDV, the basic characteristics and essential functions of the vehicle are largely designed by software – from driving dynamics to the digital ecosystem. The circular economy focuses on reducing a product's footprint by using the product itself and its components for as long as possible or reusing them as often as possible while retaining their value.

If SDV and CE are combined in the context of the automobile and current developments are extrapolated, two fundamentally different forms can be derived. These are referred to below as smartphone-on-wheels versus apartment-on-wheels, with the terms referring to the life cycle of the vehicles. The smartphone-on-wheels has a comparatively short lifespan of a few years and can therefore be designed and equipped with hardware that reflects the current zeitgeist without having to make any compromises. For CE, such a vehicle must be designed in such a way that it can be dismantled with minimal effort and all relevant components can be recycled many times in a cycle that preserves their value as much as possible. Leasing is an obvious business model. Customers bear no risk with regard to residual value, and the OEM only has the respective vehicle generation in the field for a predefined (leasing) period, which helps to reduce complexity, especially with regard to cybersecurity. The situation is completely different with the apartment-on-wheels. Here, the focus is on maintaining attractiveness and thus value stability over a life cycle of several decades. To achieve this, electronics and central processing units, for example, must be easy to expand or replace. Update and upgradeability as well as cross-product-generation modularization are becoming core competencies for OEMs. The design must be timeless, and technological innovations must be developed in such a way that they are backward compatible, that is, retrofittable for predecessor vehicles. This generates continuous sales that contribute to resilient business models. Customers receive a permanently attractive product with low depreciation, whose more expensive purchase can therefore be financed on favorable terms. Due to its longevity, this vehicle is sustainable and circular by definition. Nevertheless, wear parts must also be managed in a value-preserving cycle.

The two extremes are unlikely to exist in their pure form, but major changes in product and production structures will be necessary for a competitive transformation into circular SDV.

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